VISIONS • SCIENCE • TECHNOLOGY • RESEARCH HIGHLIGHTS

Dissertation

53

Compensation of transmitter nonlinearities using predistortion techniques

Case studies of envelope tracking amplifiers and radio-over-fibre links

Atso Hekkala

VTT

VTT SCIENCE 53

Compensation of transmitter nonlinearities using predistortion techniques

Case studies of envelope tracking amplifiers and radio-over-fibre links

Atso Hekkala

Thesis for the degree of Doctor of Science to be presented with due permission for public examination and criticism in Auditorium YB210, at University of Oulu, on the 4 April at 12 noon.

ISBN 978-951-38-8117-7 (Soft back ed.)
ISBN 978-951-38-8118-4 (URL: http://www.vtt.fi/publications/index.jsp)

VTT Science 53

ISSN-L 2242-119X
ISSN 2242-119X (Print)
ISSN 2242-1203 (Online)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT
PL 1000 (Tekniikantie 4 A, Espoo)
02044 VTT
Puh. 020 722 111, faksi 020 722 7001

VTT
PB 1000 (Teknikvägen 4 A, Esbo)
FI-02044 VTT
Tfn +358 20 722 111, telefax +358 20 722 7001

VTT Technical Research Centre of Finland
P.O. Box 1000 (Tekniikantie 4 A, Espoo)
FI-02044 VTT, Finland
Tel. +358 20 722 111, fax + 358 20 722 7001

Technical editing Maini Manninen

Kopijyvä Oy, Kuopio 2014

Compensation of transmitter nonlinearities using predistortion techniques
Case studies of envelope tracking amplifiers and radio-over-fibre links

Lähettimen epälineaarisuuksien kompensointi esivääristystä käyttäen: esimerkkitapauksina verhokäyräseuraajavahvistin ja kuituoptinen radiolinkki. **Atso Hekkala.**
Espoo 2014. VTT Science 53. 56 p. + app. 60 p.

Abstract

This thesis studies compensation of nonlinear distortions introduced in the transmitters of wireless communication systems. In particular, adaptive predistortion of the envelope tracking (ET) amplifier and the radio-over-fibre (RoF) link is considered. The main goal is to develop compensation algorithms and architectures for predistortion.

By providing a low attenuation and broadband solution, the RoF technology enables using cost-efficient and energy-efficient distributed antenna systems (DASs). Using highly efficient power amplifier (PA) structures, such as the ET amplifiers, energy efficiency of the transmitters is increased. Unfortunately, the RoF links and the ET amplifiers are inherently nonlinear. The results of this thesis indicate that these nonlinearities have to be taken into account when designing wireless communication systems. The nonlinearities can be compensated using the low complex adaptive predistortion techniques proposed in this thesis.

In this thesis, a general architecture for the predistortion of the ET amplifier is proposed. Using the architecture, the performance of predistortion is demonstrated. In addition, new time misalignment compensation methods are studied.

For the compensation of the RoF link, an extension to the conventional least mean square (LMS) algorithm for the memory polynomial-based predistortion is presented. In addition, different combinations of adaptive algorithms for predistortion are considered. From the compensation architecture point of view, the joint compensation of the RoF link and PA connected in series in the presence of nonlinear feedback is studied. Finally, feasibility of the adaptive predistortion concept is demonstrated by the measurements.

The results presented in this thesis can be applied to any wireless communications systems. The performance studies demonstrate that distortions of the RoF link and the ET amplifier can be considerably diminished using a low-complexity design. To get even better results in terms of linearity and energy efficiency, the proposed predistortion techniques can be implemented together with other techniques, such as the peak-to-average power ratio (PAPR) reduction methods.

Keywords adaptive predistortion, compensation architecture, envelope tracking amplifier, LMS, power amplifier, radio-over-fibre, RLS

Lähettimen epälineaarisuuksien kompensointi esivääristystä käyttäen
Esimerkkitapauksina verhokäyräseuraajavahvistin ja kuituoptinen radiolinkki

Compensation of transmitter nonlinearities using predistortion techniques. Case studies of envelope tracking amplifiers and radio-over-fibre links. **Atso Hekkala.**
Espoo 2014. VTT Science 53. 56 s. + liitt. 60 s.

Tiivistelmä

Tässä työssä tutkitaan lähettimen aiheuttamien epälineaaristen vääristymien kompensointia langattomissa tietoliikennejärjestelmissä. Erityisesti tarkastellaan verhokäyräseuraajavahvistimen (envelope tracking, ET) ja kuituoptisen radiolinkin (radio-over-fibre, RoF) adaptiivista esivääristystä. Päätavoitteena on kehittää esivääristysalgoritmeja ja -arkkitehtuureja.

Laajakaistaisena ja vähän vaimentavana ratkaisuna RoF-teknologia mahdollistaa kustannus- ja energiatehokkaan hajautetun antennijärjestelmän (distributed antenna system, DAS) käytön. Lähettimen energiatehokkuutta voidaan lisätä käyttämällä suuren hyötysuhteen tehovahvistinarkkitehtuureja, kuten ET-vahvistimia. Valitettavasti RoF-linkit ja ET-vahvistimet ovat epälineaarisia. Tämän työn tulokset indikoivat, että langattomien tietoliikennejärjestelmien suunnittelussa nämä epälineaarisuudet täytyy ottaa huomioon. Epälineaarisuuksia voidaan kompensoida käyttämällä tässä työssä ehdotettuja yksinkertaisia adaptiivisia esivääristystekniikoita.

Tässä työssä kuvataan ehdotus yleiseksi ET-vahvistimen esivääristysarkkitehtuuriksi. Esivääristyksen suorituskykyä demonstroidaan kyseistä arkkitehtuuria käyttäen. Lisäksi tutkitaan uusia tulosignaalien ajoitusvirheen kompensointimenetelmiä.

Lisäksi tässä työssä esitetään tavanomaisen LMS-algoritmin laajennus muistipolynomiesivääristimelle. Työssä käsitellään myös erilaisia adaptiivisten algoritmien kombinaatioita RoF-linkin kompensointia varten. Sarjaan kytkettyjen RoF-linkin ja tehovahvistimen kompensointia tutkitaan tilanteessa, jossa myös takaisinkytkentä on epälineaarinen. Lopuksi adaptiivisen esivääristyksen konseptin toteutettavuus demonstroidaan mittauksilla.

Tämän työn tuloksia voidaan soveltaa missä tahansa langattomassa tietoliikennejärjestelmässä. Suorituskykytarkastelut osoittavat, että RoF-linkin ja ET-vahvistimen aiheuttamia häiriöitä voidaan merkittävästi vähentää käyttäen yksinkertaisia kompensointimenetelmiä. Lineaarisuutta ja energiatehokkuutta voidaan parantaa implementoimalla tässä työssä ehdotettuja esivääristystekniikoita yhdessä muiden tekniikoiden, kuten huippu- ja keskiarvotehojen suhteen (peak-to-average power ratio, PAPR) pienentämisen, kanssa.

Avainsanat adaptiivinen esivääristys, kompensointiarkkitehtuuri, kuituoptinen radiolinkki, LMS, RLS, tehovahvistin, verhokäyräseuraajavahvistin

Preface

The research for this thesis has been carried out at the Communication Platforms knowledge centre of the VTT Technical Research Centre of Finland, Oulu, Finland. The work was started in 2007 and continued until 2011. The writing of this thesis was started in 2012 and finalised during the summer of 2013. This thesis has received funding mainly from two European research projects, namely FUTON and SACRA. Some work for the finalisation of the thesis has also been funded by the European Celtic-Plus project OPERA-Net-2. The supervisor of this thesis is Professor Marcos Katz from the University of Oulu. The advisor of this thesis is Docent Aarne Mämmelä from VTT.

I would like to express my gratitude to Dr Jussi Paakkari and Mr Kyösti Rautiola for providing me with the opportunity to carry out the research at VTT and giving me some free time to finalise this thesis. I am grateful to my supervisor Professor Marcos Katz for his comments and support during the project. I would also like to thank Docent Aarne Mämmelä for his guidance and help, which started immediately after I joined VTT in 2004. He has patiently and recurrently taught me the basics and introduced me to new topics in the field of telecommunication research. Special thanks go to my former supervisor Dr Seppo Karhu from the University of Oulu for the cooperation that started already during my Master's studies. I am grateful to all the co-authors of the original papers of this thesis around the Europe for the fruitful cooperation in the projects. I greatly appreciate Professors Mikko Valkama and Thomas Brazil for the pre-examination of this thesis and their valuable comments as well. Ms Outi Hiltunen from TransMate Kielipalvelut is acknowledged for excellent language revision.

At VTT, I would like to thank all my colleagues for the good atmosphere in terms of both work and coffee break discussions. Especially, I acknowledge my colleagues Mr Mika Lasanen, Dr Adrian Kotelba and Mr Pertti Järvensivu for their support and help with this thesis. I think that without the cooperation with them, this thesis would never have been finalised.

I was also privileged to receive personal grants for my doctoral studies from the following Finnish foundations: Jenny and Antti Wihuri Foundation (twice), Oulu University Scholarship Foundation, Foundation of Riitta and Jorma J. Takanen, and the Nokia Foundation. They are gratefully acknowledged.

I would like to thank my parents, siblings, parents-in-law, other relatives, and friends for their care and support throughout my life. I appreciate you a lot. My deepest gratitude goes to my wife Sinikka for her love and support and the understanding she has for me, and to our children Alina, Antton, Laura, Tuomas, and Touko for helping me to forget the business when needed. Thank you just for being there.

Oulu, January 2014 Atso Hekkala

Academic dissertation

Supervisor	Professor Marcos Katz University of Oulu Oulu, Finland
Advisor	Docent Aarne Mämmelä VTT Technical Research Centre of Finland Oulu, Finland
Pre-examiners	Professor Thomas Brazil University College Dublin Dublin, Ireland
	Professor Mikko Valkama Tampere University of Technology Tampere, Finland
Opponents	Professor Mikko Valkama Tampere University of Technology Tampere, Finland
	Professor Risto Wichman Aalto University Espoo, Finland

List of original papers

This thesis is based on the following original publications, which are referred to in the text as Papers I–V. The publications are reproduced as appendices.

I Hekkala A. & Lasanen M. 2009. Performance of adaptive algorithms for compensation of radio over fiber links. Proceedings of Wireless Telecommunications Symposium, Prague, Czech Republic, April 2009, pp. 1–5. ISBN: 978-1-4244-2588-4.

II Hekkala A., Lasanen M., Harjula M., Vieira L. C., Gomes N. J., Nkansah A., Bittner S., Diehm F. & Kotzsch V. 2010. Analysis of and compensation for non-ideal RoF links in DAS. IEEE Wireless Communications, Vol. 17, No. 3, pp. 52–59. ISSN: 1536-1284.

III Hekkala A., Lasanen M., Vieira L. C., Gomes N. G. & Nkansah A. 2010. Architectures for joint compensation of RoF and PA with nonideal feedback. Proceedings of IEEE Vehicular Technology Conference (VTC Spring), Taipei, Taiwan, May 2010, pp. 1–5. ISBN: 978-1-4244-2518-1.

IV Hekkala A., Hiivala M., Lasanen M., Perttu J., Vieira L. C., Gomes N. J. & Nkansah A. 2012. Predistortion of radio over fiber links: algorithms, implementation, and measurements. IEEE Transactions on Circuits and Systems–I: Regular Papers, Vol. 59, No. 3, pp. 664–672. ISSN: 1549-8328.

V Hekkala A., Kotelba A., Lasanen M., Järvensivu P. & Mämmelä A. 2012. Novel digital compensation approaches for envelope tracking amplifiers. Wireless Personal Communications, Vol. 62, No. 1, pp. 55–77, ISSN: 0929-6212.

Author's contributions

The author has had the main responsibility for writing all the papers. All the papers have been produced in cooperation with the colleagues of the author. In Paper I, the author has had the main responsibility for developing ideas of compensation algorithms studies and simulations. In Paper II, the author has had the main responsibility for analysing the effects of the nonlinearities on error vector magnitude and spectral regrowth as well as the compensation of them. In Paper III, the author has had the main responsibility for developing ideas of compensation architecture studies and simulations. In Paper IV, the author has had the main responsibility for developing adaptive predistortion algorithms, studying different combinations of the algorithms, and verifying the compensation performance by measurements. In Paper V, the author has had the main responsibility for proposing a new predistorter approach, demonstrating its performance, developing recursive solutions of time misalignment compensation with adaptive predistorter, and demonstrating in a detailed manner the performance of the time misalignment compensation methods.

Contents

Symbols and abbreviations

$a_{pm,g}$	Coefficient of generalised memory polynomial model
c_{pm}	Coefficient of memory polynomial model
F_m	Polynomial function
G	Memory length in leading and lagging terms
$h_p(i_1, \ldots, i_p)$	p^{th}-order Volterra kernel
M	Memory length
P	Nonlinearity order
$x(n)$	Input signal at discrete time sample n
$y(n)$	Output signal at discrete time sample n
3GPP	Third generation partnership project
ACLR	Adjacent channel leakage ratio
ACP	Adjacent channel power
AWGN	Additive white Gaussian noise
BER	Bit error rate
CALLUM	Combined analogue locked loop universal modulator
DAS	Distributed antenna system
DC	Direct current
DL	Downlink
DSP	Digital signal processor
EER	Envelope, elimination and restoration
ET	Envelope tracking
EVM	Error vector magnitude

FUTON	Fibre-optic networks for distributed extendible heterogeneous radio architectures and service provisioning
IF	Intermediate frequency
I/Q	In-phase / quadrature
LINC	Linear amplification with nonlinear components
LIST	Linear amplification by sampling techniques
LMS	Least mean square
LS	Least squares
LTI	Linear time-invariant
LUT	Look-up-table
MIMO	Multiple-input multiple-output
MP	Memory polynomial
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
OPERA-Net-2	Optimising power efficiency in mobile radio networks 2
PAPR	Peak-to-average power ratio
PA	Power amplifier
RF	Radio frequency
RLS	Recursive least squares
RoF	Radio-over-fibre
SACRA	Spectrum and energy efficiency through multi-band cognitive radio
UL	Uplink
UMTS	Universal mobile telecommunications system
VS NLMS	Variable step size normalised least mean square
WLAN	Wireless local area network

1. Introduction

1.1 Motivation of the thesis

The trend in wireless communication is to offer to end users wireless services similar to those offered through wired connections. Due to that, there is an ever increasing need for higher data rates. This, in turn, is enabled by using larger bandwidths and advanced communication methods such as multiple-input multiple-output (MIMO) techniques. In addition, due to the high data rates, there is a need to exploit spectrally efficient modulation techniques such as orthogonal frequency division multiplexing (OFDM), where both the phase and the amplitude of the signal carry information. These systems are very sensitive to the nonlinear distortions introduced by the analogue parts, especially at the transmitter side. To avoid the significant degradation of the signal quality at the transmitter, the requirements of the analogue radio frequency (RF) components such as power amplifier (PA) are becoming stricter. On the other hand, the effects of the nonlinearities should also be taken into account in the design of the transceivers (Fettweis et al. 2007). There are also other impairments, such as I/Q imbalance, phase noise, and DC offset, which may limit the performance of the wireless communication (Fettweis et al. 2007, Gregorio 2007). However, these are not addressed in this thesis.

In the presence of the nonlinear multiantenna transmitters, emerging techniques such as non-contiguous carrier aggregation and simultaneous multi-radio-access-technology transmission introduce specific challenges (Bassam et al. 2009, Gregorio et al 2011). Their requirements for linearity over the very wide bandwidths are even more demanding. In addition, crosstalk between different MIMO branches may affect severely system performance.

The nonlinear effects are usually classified as signal in-band and out-of-band distortions. The in-band and out-of-band distortions are usually measured as bit error rate (BER) or error vector magnitude (EVM) and adjacent channel power (ACP), respectively. The EVM requirements are defined in standards, see e.g., (Holma & Toskala 2011) or the requirements of the Third Generation Partnership Project (3GPP) standardisation in (3GPP TS36.104). Correspondingly, communication standards limit the out-of-band emissions by specifying adjacent channel leakage ratio (ACLR) or spectrum and spurious emission masks. The ACLR refers to the ratio of the power on the assigned channel to the power on the adjacent channel. The spectrum emission mask is another specification which sets maximum power levels relative to the assigned channel close to the signal band. Further away from the signal band, the spurious emission masks are used to limit, for example, harmonics emissions.

Energy efficiency has become an important parameter in wireless communications. Due to its large power consumption, the PA is a critical component in the transmitter (Correia et al. 2010, Auer et al. 2011). This is particularly important for orthogonal frequency division multiple access (OFDMA) because of its large peak-to-average power ratio (PAPR) of the transmitted signal. Therefore, it is essential to increase the efficiency of the PA. Generally speaking, highly efficient PAs are nonlinear (Kim et al. 2010, Lavrador et al. 2010); there is a trade-off between their efficiency and linearity. Several different PA structures have been studied which aim to increase the efficiency of the PA, see e.g., (Kenington 2000, Raab et al. 2002, Cripps 2006, Eron et al. 2011).

In addition to using a highly efficient PA structure, energy consumption of the PA can be reduced by signal design. In signal design, the PAPR of the signal is reduced, i.e., the fluctuation of the transmitted signal envelope is reduced. Several methods for the PAPR reduction of the OFDM signal have been reported in the literature, see e.g., (Han & Lee 2005, Jiang & Wu 2008). Another approach to signal design is based on signal transformation (Thompson et al. 2008). In this technique, prior to amplification by the PA, the signal is modified to have only phase modulation. After that, the signal can be amplified with high efficiency due to the low PAPR of the phase-modulated signals. An inverse transformation is needed at the receiver. Earlier, signal design has also been referred to by the term data predistortion, see e.g., (Fettweis et al. 2007, Karam & Sari 1991). Signal design is beyond the scope of this thesis and therefore not considered anymore here.

To reduce the distortions produced in the highly efficient but nonlinear PAs, the PAs can be linearised (Katz 2001, Raab et al. 2002, Kenington 2002). Predistortion is one of the most widely studied compensation, or linearisation, methods (Ghannouchi & Hammi 2009, Lavrador et al. 2010). In predistortion, the idea is to add a compensation block, i.e., a predistorter, prior to the PA; see Figure 1.1, where a simplified block diagram of the transmitter used in this thesis is shown. It should be mentioned that, in general, predistortion can take place at digital baseband, analogue baseband, or analogue RF. However, this thesis focuses on the digital baseband predistortion. The predistorter is a nonlinear inverse filter which aims to be precisely complementary to the nonlinear characteristics of the PA so that the combined transfer function of these two components is at least almost linear. Note the difference between the predistorter and equaliser, the latter of which is used to reverse the distortions incurred by a signal transmitted through a channel. Predistortion can also be interpreted as a type of signal design to adapt for the nonlinearities of the PA.

It is well known that the nonlinear characteristics of the PA vary in time due to, for example, leakage current, ageing of the components, and thermal effects. In addition, in the calibration phase of the system, a compensator should be adapted to the nonlinearity. This is because not all the PAs have the same nonlinear characteristics due to variations of the manufacturing processes. Therefore, adaptive compensation of the nonlinearities is needed. For adaptive compensation, several algorithms and architectures have been proposed (Eun & Powers 1997, Kim & Konstantinou 2001, Widrow & Walach 1996). For adaptation, feedback from the output of the PA is required, see Figure 1.1. In practice, the feedback is nonideal; for example, it has a delay and it may be nonlinear.

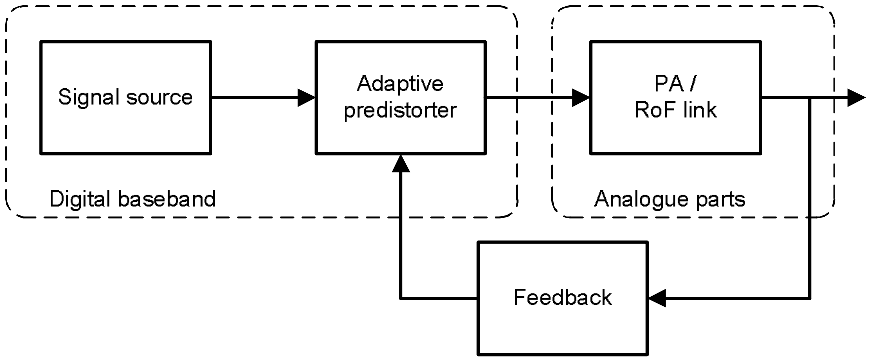


Figure 1.1. Simplified block diagram of a transmitter with an adaptive predistorter.

To achieve high data rates in cellular networks, small cells are used. Due to that, a large number of conventional and expensive base stations are required. Moreover, the small cells increase intercell interference and the number of handovers limiting the system capacity. As a solution to the above-mentioned problems, a distributed antenna system (DAS) has been proposed (Al-Raweshidy & Komaki 2002, Gomes et al. 2012).

In the DAS, the conventional base stations are replaced by simple remote antenna units, which are connected to a central unit via radio-over-fibre (RoF) links, i.e., analogue RF signals are transmitted through the fibre. In such a system, the end user can be connected simultaneously to several physically separately located remote antenna units exploiting distributed MIMO communication. Most of the signal processing is handled jointly in the central unit. Therefore, the remote antenna units can be simple and inexpensive, containing only PAs and antennas. Intercell interference mitigation and frequent handovers are handled easily by the joint signal processing in the central units. As a part of coordinated multipoint transmission and reception, the DAS concept is going to be considered in the current and future 3GPP standards, see e.g., (Lee et al. 2012). The RoF technology has been used in radio communication already a few decades (Harvey et al. 1991). The benefits of it are low attenuation and enormous bandwidth. However, nonlinear distortions stemming from its optoelectronic devices may significantly degrade the transmitted signal quality (Shah & Jalali 2005, Yao 2009).

Considering DASs, there may be a need to compensate the analogue parts of the whole transmitter chain, i.e., in addition to the nonlinearities of the conventional transmitter, the nonlinear components in the RoF links should be compensated. This is a more challenging task. The most of the discussed techniques are also applicable to other components than PAs, such as optical transmitters in the RoF links (Katz 2001, Shah & Jalali 2005). Since the nonlinear distortions of the optical modulation usually dominate those of the photo detection device, the RoF link performance is mainly dependent on the optical transmitter (Cox 2004). Moreover, in the DAS, additional propagation delays due to the use of the distributed antennas may need to be compensated (Moon & Sedaghat 2006, Hekkala et al. 2012).

Several advantages can be obtained by compensating the distortions of the nonlinear components. First, inexpensive but nonlinear components can be used. In addition, with given nonlinear components, better energy efficiency of the whole system can be obtained. Moreover, from the transmitted signal point of view, compensation reduces both the in-band (measured with EVM and BER) and out-of-band (measured with ACP) distortions. Finally, when reducing out-of-band distortions, adjacent signals or channels can be located closer to each other in the frequency domain.

Nonlinear distortions can also be compensated at the receiver side (Gregorio 2007, Fettweis et al. 2007). However, it is intuitively reasonable to compensate the distortions already at the transmitter close to the place where they are introduced. When the compensation is performed at the receiver, the signal and distortions go through the time-variant channel, making the compensation even more complicated. In addition, the out-of-band distortions cannot be compensated at the receiver, i.e., after the channel where the distortions already have an influence on others.

1.2 Contributions of the thesis

In this thesis, compensation of nonlinear distortions in wireless communication systems is studied. The focus is to compensate, using predistortion techniques, a nonlinear PA and the RoF link needed in DASs. This thesis aims at developing simple compensation algorithms and architectures for predistortion. The research methods include analysis, simulations, and measurements.

When considering a nonlinear PA, we propose a general predistortion architecture, which can be applied to a wide class of envelope tracking (ET) amplifiers, see Figure 1.2. The architecture is analysed and compared against the state-of-the-art architecture presented earlier in the literature. With respect to the state-of-the-art architecture, Wang et al. (2005) and Jeong et al. (2009) have studied predistortion in which the predistorter affects only the signal to be transmitted, and therefore it is not a general one. Furthermore, using the proposed architecture, the performance of the optimal and adaptive predistorters for the linear filters and the ET amplifier are demonstrated. In addition, to study the convergence of the time misalignment compensation method developed, recursive solutions of the algorithm are considered. Earlier studies (Wang et al. 2005) considered only the one-shot compensation method, which cannot necessarily be applied because of the use of the simplified predistorter and amplifier models. The performance of the time misalignment compensation methods for linear filters and the ET amplifier with optimal and adaptive predistorters are demonstrated in a detailed manner.

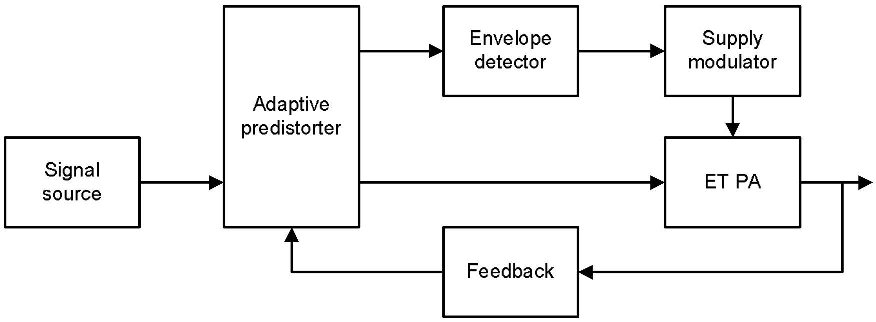


Figure 1.2. Simplified block diagram of an ET PA structure including the adaptive predistortion concept.

For the RoF link case, we study adaptive algorithms for the compensation of the nonlinearities using a memory polynomial (MP)-based predistorter, see Figure 1.1. This thesis further develops the predistortion approaches presented in (Fernando & Sesay 2002, Ding et al. 2004). The effects on EVM and ACP stemming from the nonlinear RoF link are analysed. In (Zhou & DeBrunner 2007), a least mean square (LMS) algorithm is used for the compensation of the nonlinearity with memory. However, Morgan et al. (2006) have stated that the LMS algorithm is not suitable for the adaptive compensation due to its slow convergence. Chen et al. (2006) have considered different step sizes for the LMS algorithm, but no details on the algorithm have been given. In this thesis, extensions that enable using the LMS algorithm for the compensation of the nonlinearity with memory are introduced in detail. In addition, different combinations of the adaptive algorithms for predistortion are considered. Moreover, in the presence of nonideal feedback, the architectures for the joint compensation of the RoF link and the PA connected in series are studied. Finally, the performance of the adaptive predistortion is verified by measurements.

This thesis is based on five original publications, which are summarised in Chapter 3. Other supplementary compensation-related publications of the author include (Hekkala et al. 2012, Hekkala et al. 2010, Hekkala et al. 2008a, Hekkala et al. 2008b, Kotelba et al. 2008, Lasanen et al. 2008).

1.3 Outline of the thesis

The rest of the thesis is organised as follows. In Chapter 2, the relevant literature on the compensation of nonlinearities at the transmitter is reviewed. A summary of the original articles is presented in Chapter 3. In Chapter 4, the main findings, limitations, and recommendations for future work are discussed. Finally, the conclusions of the thesis are presented in Chapter 5.

2. Review of nonlinear compensation

2.1 Highly efficient transmitters

To achieve energy-efficient transmission in wireless communication, three different methods are considered, namely highly efficient transmitters, signal design, and nonlinearity compensation. The classification of these methods is shown in Figure 2.1. Note that all the three methods can be combined together. For example, in Paper V, the predistortion of the envelope tracking amplifier is discussed. In this section, highly efficient transmitters are discussed. As already mentioned, the signal design shown in the figure is beyond the scope of this thesis. Moreover, the compensation methods will be discussed in more detail in Section 2.3.

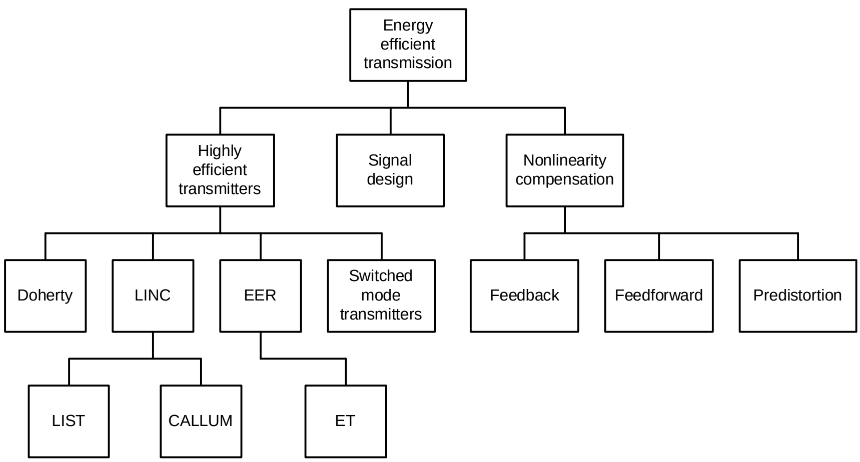


Figure 2.1. Classification of energy-efficient transmission possibilities.

The most widely used energy-efficient transmitters can be classified as follows: linear amplification with nonlinear components (LINC), including combined analogue locked loop universal modulator (CALLUM) and linear amplification by sampling techniques (LIST); Doherty technique; Kahn technique (also known as envelope, elimination and restoration (EER)), including envelope tracking (ET); and switched-mode transmitters. In the following, these methods are briefly reviewed. For more information, see, for example, review articles (Raab et al. 2002, Eron et al. 2011) and books (Kenington 2000, Cripps 2006).

In the Doherty architecture, the efficiency of the transmitter can be increased by using two amplifiers typically biased in B and C classes in cooperation (Doherty 1936, Raab et al. 2002). A class-A amplifier is biased about the centre of the input signal swing, meaning that it conducts current throughout the entire cycle. In the class-B amplifier, the output flows for half of the input signal cycle, whereas in the class-C, the amplifier conducts for only a short portion of each input cycle, making it more efficient and nonlinear than the class A and B amplifiers. More information about the amplifier classes in general can be found in (Kenington 2000). At low signal levels, only the first, i.e., the class-B amplifier is active and its efficiency is improved because the second amplifier acts as an active load for the first amplifier. At high signal levels, both amplifiers are active.

The first idea of the LINC or outphasing method has been proposed in (Chireix 1935). Cox (1974) has introduced this concept for use at microwave frequencies and named it the LINC. In the LINC method, the input signal is divided into two constant envelope signals, both having only phase variation. These angle-modulated signals are amplified using highly efficient amplifiers, and the output signal is obtained by summing the amplified signals together. Highly efficient amplifiers are usually strongly nonlinear. To correct the LINC imperfections, some modifications of the LINC technique have been proposed, including the LIST (Cox 1975) and CALLUM (Bateman 1992)

In the EER technique (Kahn 1952), the input signal is divided into envelope and phase-modulated signal parts. Then, the phase-modulated signal is amplified using a highly efficient amplifier at a saturation level. The DC supply of the amplifier is modulated by the envelope signal and thus the envelope is restored to the amplified phase-modulated output signal.

The ET technique is a modification of the EER architecture (Raab 1975). In the ET architecture, the amplifier operates in a linear region. To achieve high efficiency, the supply voltage of the amplifier is varied dynamically according to the envelope of the signal. The ET amplifiers will be considered in more detail in Section 2.5.

Improvements in efficiency can also be obtained by using switched-mode amplifiers (Sjöland et al. 2010, Nielsen & Larsen 2007). In the switched-mode amplifier technology, transistors are used in saturation, i.e., the amplifier is always either working at its peak efficiency or entirely switched off. Switched-mode amplifiers cannot amplify complex modulations, such as OFDM. To support the amplification of the complex modulations, e.g., delta-sigma, RF pulse width, burst, or supply voltage modulations can be used. Supply voltage modulation is similar to the EER technique.

2.2 Models for nonlinear power amplifiers

In practice, the power amplifier operates more or less in the nonlinear region, i.e., the response of the PA is nonlinear. For that reason, when studying the compensation of the nonlinear PA, it is essential to use an accurate enough model for the nonlinearities. In the literature, the nonlinear PA models are usually classified to behavioural or empirical models and the models based on the physical descriptions of the PA (Kenington 2002, Pedro & Maas 2005). In the latter, electric components (e.g., inductors and capacitors) that comprise the PA are modelled. The detailed PA internal structures need to be modelled, and therefore the simulations using the model based on the physical descriptions of the PA could be time consuming. In addition, it is challenging to model, for example, memory effects of the PA. These models are appropriate to circuit-level simulations (Pedro & Maas 2005). In the behavioural modelling, the PA is treated as a black box, i.e., the internal structure of the PA is not known. The modelling is based only on the observations of the input and output signals of the PA. The behavioural modelling approach is widely used in the literature, see e.g., (Pedro & Maas 2005, Hammi et al. 2010, Tehrani et al. 2010, Ghannouchi & Hammi 2009) and references therein. Figure 2.2 shows a simplified diagram of the PA model classification. In this thesis, these models will be considered in more detail in the following.

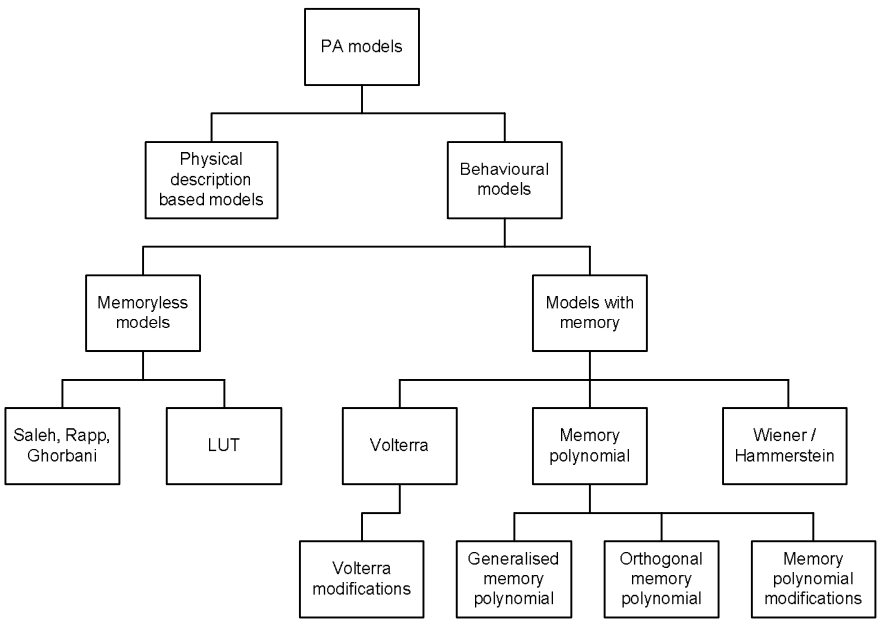


Figure 2.2. PA model classification.

The nonlinear PA models can also be classified as memoryless models and models with memory. Several conventional memoryless PA models can be found in the literature (Saleh 1981, Ghorbani & Sheikhan 1991, White et al. 2003). In addition, basic look-up-table (LUT)-based models can also be considered as memoryless modelling (Ghannouchi & Hammi 2009). In the LUT approach, the input-output mapping of the nonlinear model is pre-calculated and stored in the table entries in memory. Due to the wide bandwidths used in modern wireless communication systems, the PA's nonlinearity depends on frequency. The current signal sample at the output of the PA also depends on the past input samples. This means that the memory effects of the PAs have to be taken into account when modelling the PA (Kenington 2000, Ku & Kenney 2003, Hammi et al. 2010).

The Volterra series is a general and most comprehensive analytical model for weak nonlinearities with memory (Schetzen 1980, Jeruchim et al. 2000). The Volterra series are characterised by Volterra kernels. The Volterra model can be presented as follows:

$$y(n) = \sum_{p=1}^{P} \sum_{i_1=1}^{M} \dots \sum_{i_p=1}^{M} h_p(i_1, \dots, i_p) \prod_{j=1}^{p} x(n - i_j) \quad (1)$$

where $x(n)$ and $y(n)$ represent the input and output of the model, respectively, $h_p(i_1, \dots, i_p)$ is the p^{th}-order Volterra kernel, P is the nonlinearity order, and M is the memory length. At least for higher order nonlinearities, the kernels are computationally complex and, for the predistortion, p^{th}-order inverse of the Volterra model is difficult to construct (Ding et al. 2004). The inverse may not even exist or it exists only in a limited amplitude range (Schetzen 1980). Due to the high complexity, the Volterra series are inappropriate for the practical modelling of the PA (Tehrani et al. 2010, Ding et al. 2004, Cheong et al. 2012). To reduce the complexity and improve the performance, several modifications of the Volterra model have been proposed in the literature, see e.g., (Pedro & Maas 2005, Zhu et al. 2008a, Hammi et al. 2010, Tehrani et al. 2010, Ghannouchi & Hammi 2009).

The Wiener model can be seen as a special case of the Volterra model (Clark et al. 1998). It consists of a linear time-invariant (LTI) filter followed by a nonlinear memoryless block. Usually, the memoryless nonlinearity is modelled using a polynomial function or LUT (Morgan et al. 2006, Ghannouchi & Hammi 2009). The Wiener modelling has two advantages (Ding et al. 2004). First, for the predistorter, it is possible to find an exact inverse of the Wiener PA model. Second, the Hammerstein structure can be used as a predistorter of the Wiener PA model. In the Hammerstein approach, contrary to the Wiener modelling, the system is composed of a nonlinear memoryless block followed by an LTI filter. In the Wiener-Hammerstein model there is an LTI filter followed by a nonlinear memoryless block, which is in turn followed by another LTI filter; see the principle of the Wiener-Hammerstein model in Figure 2.3.

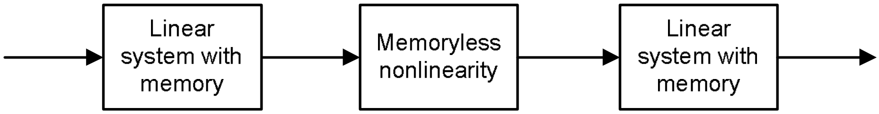


Figure 2.3. Principle of the Wiener-Hammerstein model.

The memory polynomial (MP) model is another special case of the Volterra model (Kim & Konstantinou 2001, Ding et al. 2004). It is a reduction of the Volterra model where only diagonal terms are kept. The output of the MP model can be described by (Ding et al. 2004)

$$y(n) = \sum_{p=1}^{P}\sum_{m=0}^{M} c_{pm}x(n-m)|x(n-m)|^{p-1} \tag{2}$$

where c_{pm} is the coefficient of the MP model. Figure 2.4 shows a principle of the MP modelling approach with polynomial functions F_m; the polynomial functions F_m being

$$F_m(n) = \sum_{p=1}^{P} c_{pm}x(n)|x(n)|^{p-1}. \tag{3}$$

The same as in the Volterra modelling, it is difficult to obtain an exact inverse of the MP model. Fortunately, another MP can be used for the inverse model.

Hammi et al. (2010) have reported that the MP approach suffers from instability problems. That is because the matrices used, for example, in the least-squares solution have high condition numbers. The high condition number in the matrix makes its inversion calculation more unstable to the slight disturbances of the input parameters. Often, only odd order terms are used in the MP modelling (Ding et al. 2004, Morgan et al. 2006, Nader et al. 2011). Some performance improvements, i.e., improving the modelling accuracy while keeping the number of the coefficients fixed, can be achieved using also even terms in the predistorter (Ding & Zhou 2004). However, this is achieved at the cost of implementation complexity (Hekkala et al. 2012, Tehrani et al. 2010). The MP modelling approach is widely used in the field of PA modelling and predistortion studies (Kim & Konstantinou 2001, Ding et al. 2004, Ma et al. 2011, Kim et al. 2008, Nader et al. 2011).

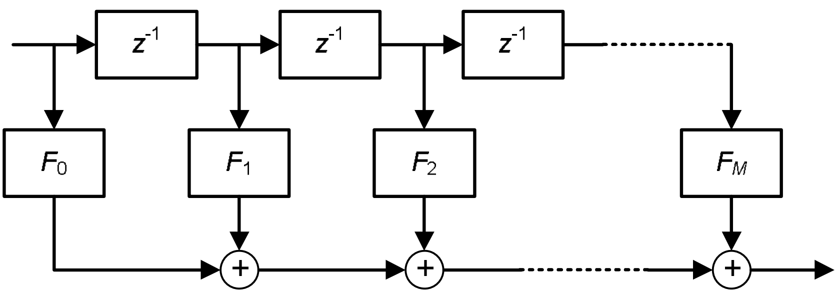


Figure 2.4. Memory polynomial modelling.

There are also many modifications of the MP modelling approach. In a generalised MP, the MP is extended by adding more cross-terms between the signal and its leading and lagging terms, i.e., the terms coming before and after it, respectively (Morgan et al. 2006). More degrees of freedom for the coefficients are achieved. The generalised MP model can be expressed as

$$\begin{aligned} y(n) = & \sum_{p=1}^{P}\sum_{m=0}^{M} a_{pm,0}x(n-m)|x(n-m)|^{p-1} \\ & + \sum_{p=1}^{P}\sum_{m=0}^{M}\sum_{g=1}^{G} a_{pm,g}x(n-m)|x(n-m-g)|^{p-1} \\ & + \sum_{p=1}^{P}\sum_{m=0}^{M}\sum_{g=1}^{G} a_{pm,g}x(n-m)|x(n-m+g)|^{p-1} \end{aligned} \quad (4)$$

where $a_{pm,g}$ is the coefficient of the generalised MP model and G corresponds to the amount of memory in the leading and lagging terms.

Tehrani et al. (2010) have compared a few behavioural PA models including the MP, generalised MP, and three different Volterra-based models. The generalised MP has the best trade-off between accuracy and complexity. An orthogonal MP (Raich et al. 2004) that uses a set of orthogonal basis functions has been proposed to alleviate the numerical instability problems of the MP approach. In (Hammi et al. 2010), the orthogonal MP has been reported to outperform the MP in the modelling accuracy. Hammi et al. (2010) have also proposed a hybrid MP model, which is a combination of the MP and modified LUT models.

In a recent article, Rawat et al. (2012) have proposed a three-layered MP model based on neural networks. There are three polynomials one after the other including an adaptive bias for the second polynomial. Only the last one includes memory; the others model only the memoryless nonlinearity. Therefore, it is possible to have different nonlinearity orders with and without memory. This model has a comparable performance in terms of modelling accuracy as the MP and orthogonal MP, but with lower complexity as well as better matrix conditioning.

2.3 Compensation architectures and algorithms

Feedback, feedforward, and predistortion are the most common techniques of the compensation of the nonlinear transmitter (Katz 2001, Raab et al. 2002, Kenington 2002). The principle of the feedback technique is to force the PA output signal to follow the input signal by feeding the output signal back to the input (Black 1934). The feedback technique is very sensitive to the delays of the amplifier and associated signal processing components (Katz 2001). For that reason, it is not suitable for the compensation of modern wide bandwidth transmitters. However, wider bandwidths can be handled using, for example, a Cartesian feedback technique (Raab et al. 2002).

Seidel (1971) has proposed the first modern feedforward compensation technique following the early concept of Black from 1928. The basic idea of the feedforward technique is to have an additional error amplifier whose output is subtracted from the main output signal. The error amplifier is driven by the distortions produced in the main amplifier. See the principle of the feedforward technique in Figure 2.5.

The feedforward technique is applicable to wider bandwidths than the feedback technique. The power efficiency of the entire transmitter may be reduced due to the use of the additional amplifier (Lavrador et al. 2010). In addition, time mismatches between the parallel branches may reduce the performance. However, research on feedforward compensation is still ongoing. For example, in a recent paper, Shahed et al. (2012) have proposed a scheme where bulky RF components can be replaced by more flexible DSP circuitry.

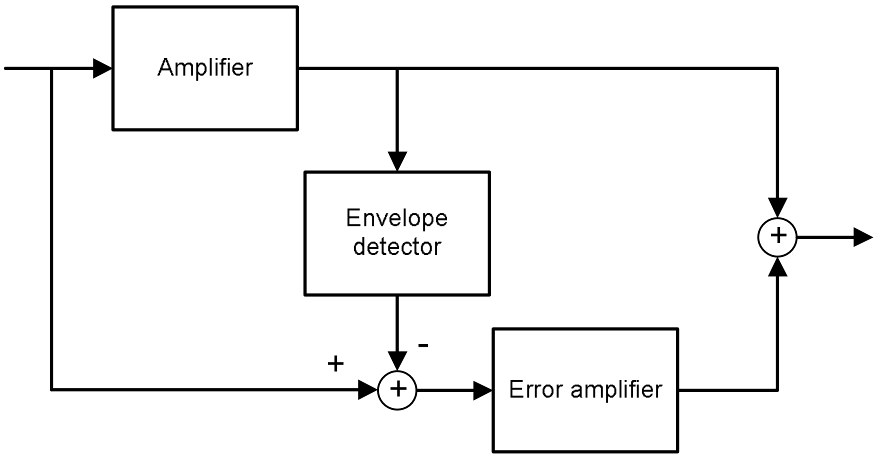


Figure 2.5. Simplified principle of the feedforward technique.

Macdonald (1959) has proposed the predistortion concept in audio communication as an alternative to the feedback technique. The feedback technique was inconvenient, for example, for the compensation of the nonlinear distortions of the loudspeaker. In the predistortion concept, a nonlinear functional block, i.e., a predistorter, is inserted prior to the amplifier so that the combined transfer function of these two components is almost linear, see Figure 1.1. In other words, the predistorter behaves as an inverse of the amplifier. In the same paper, Macdonald (1959) also discusses postdistortion, i.e., the compensator is located after the amplifier. The postdistortion approach was not suitable for the compensation of the loudspeaker either (Macdonald 1959).

The predistorter can be accomplished in the analogue domain at radio, intermediate, or baseband frequencies, or in the digital domain at baseband (Kenington 2002). The analogue predistortion has some advantages such as low cost and a simple structure (Roselli et al. 2003, Lee et al. 2009). For very high bandwidth RoF applications such as fibre cable television systems, analogue predistorters are also applicable, see e.g., (Shen et al. 2010, Shah & Jalali 2005, Sadhwani & Jalali 2003). However, more flexibility is obtained using a digital predistorter handled by a digital signal processor (DSP) and, in addition, an adaptive predistorter may be difficult to implement in the analogue domain. For that reason, the digital predistortion approach has gained much attention in the recent literature (Ding et al. 2004, Morgan et al. 2006, Anttila et al. 2010, Cheong et al. 2012). The digital predistortion scheme will be discussed in more detail in Section 2.4.

When designing the adaptive predistorter, the two most used learning architectures can be applied: direct and indirect learning. Both of the learning architectures are special cases of the inverse control structure (Widrow & Walach 1996, Paaso & Mämmelä 2008). In the direct learning architecture (Kang et al. 1999, Kim & Konstantinou 2001), the amplifier model is first identified. Then, using this model, the inverse of it is computed. Finally, the inverse is used as the predistorter.

In the indirect learning architecture, the inverse of the amplifier is first identified and this inverse is then used as the predistorter (Psaltis et al. 1988, Eun & Powers 1997). Due to possibly highly noisy amplifier output, the inverse model may converge to biased values (Zhou & DeBrunner 2007). In addition, commutation of the nonlinear blocks is not valid in general (Mämmelä 2006). In the indirect learning architecture it means that placing a copy of the inverse, i.e., the postdistorter in front of the amplifier as the predistorter may degrade the compensation performance (Zhou & DeBrunner 2007). However, Jiang & Wilford (2010) have stated that, under certain conditions, if there is a postdistorter, then it behaves also as a predistorter. See also (Schetzen 1976), where the p^{th}-order post-inverse of a given system has been shown to be identical to its p^{th}-order pre-inverse. In other words, the postdistorter and predistorter are equivalent and hence the predistortion using the indirect learning architecture is justified. The indirect learning is more popular than the direct learning architecture, even if the latter can perform better, see e.g., (Zhou & DeBrunner 2007, Paaso & Mämmelä 2008). That is because the amplifier model is needed to be modelled in the direct learning architecture and therefore the computational complexity of the predistortion is much larger than in the indirect learning architecture (Jiang & Wilford 2010, Cheong et al. 2012).

It is well known that the superposition theorem is not generally valid in nonlinear systems. Therefore, it is important to properly normalise the input and output samples in the adaptation. The normalisation is dependent on the expected gain of the linearised PA (Zhu et al. 2008a). To avoid the need of different scaling factors, the expected gain should be chosen at a targeted maximum output power level so that the PA input signals with and without a predistorter reach the same maximum output power.

In practical systems, the fast changes of the power levels due to power control have to be taken into account. The PA may have different nonlinear characteristics at the different power levels. Therefore, the predistorter has to be adjusted to these rapidly enough. Another solution for this is to create a parameter table for the different power levels. Due to the different power levels used in the transmission, the temperature of the PA changes. For example, the transistors in the PA provide different voltages in different temperatures, which affect the gain of the PA (Vuolevi et al. 2001, Boumaiza & Ghannouchi 2003). This distortion can be mitigated not only by adaptive predistortion but also by temperature compensation, see e.g., (Chen & Yuan 2011) and references therein.

Adaptive algorithms are used to adjust the adaptive model, e.g., the predistorter, so that the desired response of the system is achieved. A mean square error criterion is a basic criterion for most of the adaptive algorithms, i.e., the goal is to minimise the mean value of a squared error signal (Claasen & Mecklenbräuker 1985). There are two approaches, the least squares (LS) method and the gradient method, that are typically used to achieve the minimum (Claasen & Mecklenbräuker 1985). In the LS method, the best possible estimate in the LS sense is determined using the available data at a certain time instant. In the gradient methods, the optimum is searched iteratively with the directions defined by the gradient of the function at each time instant. The LS method has been widely used in the compensation literature, see e.g., (Ding et al. 2004, Zhu et al. 2008a, Afsardoost et al. 2012, Rawat et al. 2012). The LMS algorithm is a basic, widely used recursive gradient algorithm (Widrow & Hoff 1960). As another recursive algorithm, the recursive least squares (RLS) solution provides faster convergence rate and more robust performance against the variations in the eigenvalues of the input signal covariance matrix (Haykin 2002). However, the computational complexity is significantly increased. Eun & Powers (1997), Fernando & Sesay (2002), and Choi et al. (2009) can be given as examples of the papers where the RLS solution is used.

Due to its low complexity, the LMS algorithm has been commonly used for adaptive digital filtering in linear systems. The main limitation of the LMS algorithm is the trade-off between a steady-state misadjustment and, especially when the eigenvalues of the signal covariance matrix vary a lot, slow convergence in adaptation (Proakis 1995). Both of them are governed by a single step size parameter. Proakis (1995 p. 643) has discussed the step size dependency on the signal power. The upper limit of the step size is inversely proportional to the signal power.

In addition to the linear systems, the LMS algorithm has been widely used for the compensation of nonlinear systems (Zhou & DeBrunner 2007, Tan & Jiang 2001, Kim et al. 2006, Li et al. 2009, Younes & Ghannouchi 2012). Note that in order to extract a nonlinear system model using linear system identification algorithms such as LMS, RLS or LS, the model has to be linear in parameters. Zhou & DeBrunner (2007) and Kim et al. (2006) have used the LMS algorithm for the adaptation of the predistorter in the direct learning and indirect learning architectures, respectively. In all of these papers, only one step size of the LMS algorithm has been used for all the nonlinearity orders.

In (Celka et al. 2001), the scaling of the step size according to the signal power is considered when identifying a nonlinear Wiener system. In addition, in (Chen et al. 2006), different step sizes of LMS adaptation for the 1st and 3rd order memoryless polynomial predistorters have been considered. However, no further details about the step sizes or their descriptions have been given.

2.4 Predistortion

Predistortion has originally been divided into two basic categories, data and signal predistortion (Karam & Sari 1991). As mentioned in Section 1, data predistortion has actually meant signal design and therefore is not considered in this thesis. Signal predistortion is based on the approximation of the PA response, which is here referred to simply as predistortion.

As already stated, the digital predistorter operates in the digital domain at baseband, achieving the flexibility for the adaptive compensation of the nonlinear amplifier. It may or may not include memory. When including memory, the output of the predistorter depends not only on the current input but also on the past inputs. In other words, it is then able to handle frequency-dependent nonlinearities. Many predistorters are closely related to the PA models already presented in Section 2.2.

Ding et al. (2004) have studied predistortion using the MP structure originally proposed in (Kim & Konstantinou 2001). The MP predistorter has been shown to be a robust predistorter for several modifications of the Wiener models and the MP model. To improve the compensation performance, reduce the complexity, or increase the stability of the MP predistorter, several modifications of the MP predistorter have been proposed in the literature.

By adding some cross-terms between the signal and the lagging or leading terms, Morgan et al. (2006) have proposed a generalised MP predistorter. The better performance in terms of ACP has been achieved with only a little increase of complexity. To increase the numerical stability of the predistorter, orthogonal polynomials have been proposed in (Raich et al. 2004). However, this is achieved with increased complexity (Hammi et al. 2010). A joint LUT and polynomial predistorter, where the LUT size and polynomial order can be smaller, has been proposed in (Chen et al. 2006). In this combination, the high complexity of high order polynomials and the poor algorithm convergence of the LUT can be avoided. In (Hammi et al. 2010), the same kind of approach has been proposed using the hybrid combination of the nested LUT and MP. Another LUT-polynomial predistorter has been proposed in (Kim et al. 2008) where the LUT part compensates first the memoryless nonlinearity of the amplifier. Then using a parallel Hammerstein predistorter, which is actually a special case of the MP (Ding et al. 2004), the memory effects are compensated. The nonlinearity order of the MP can be reduced due to already compensated memoryless nonlinearities.

To improve the performance and reduce the complexity, Afsardoost et al. (2012) have proposed a switched-mode predistorter for a highly nonlinear power amplifier. In this structure, the input signal space is divided into different regions, and for each region, there is a predistortion function, e.g., the generalised MP, with a different set of parameters. Due to different regions, the nonlinearity order can be decreased compared to the case of the conventional one-region predistorter. The complexity is decreased while the performance is increased. The generalised MP and Volterra series-based predistorters achieve equal performance. However, the training of the predistorter needs more samples due to several different predistorters to be trained for each of the regions.

Another view on reducing the nonlinear order of the polynomial predistorter has been introduced in (Cheong et al. 2012) by proposing a piecewise linear predistorter with memory. Again, the input signal space is divided into different regions, but now the predistorter for each region is modelled using linear filters with memory. Compared to the MP and generalised MP predistorters, the piecewise linear predistorter achieves a better performance in terms of ACP and EVM. The MP and generalised MP exhibit an equal performance. In addition, the piecewise linear predistorter is more robust against measurement noise, which is mentioned as a major problem in the indirect learning architecture.

Rawat et al. (2012) have proposed one way to reduce the complexity of predistortion by adding three polynomials in a consecutive manner, where the first two polynomials are memoryless and the last one has memory. The training of the three polynomials is done by exploiting neural networks. The polynomials can have different nonlinearity orders and memory length, making it possible to find a good compromise between the complexity and performance. The proposed predistorter has been compared to the MP and orthogonal MP-based predistorters: a comparable performance has been achieved but with a lower complexity. In addition, it is noticed that the MP structure is much less complex than in the orthogonal MP predistorter.

A systematic and general structure of a Volterra-based predistorter by using separable functions has been proposed in (Jiang & Wilford 2010). This structure has been derived independently of the PA models using approximations with separable functions. Therefore, the approach is able to compensate a large variety of the PA models, which means that the same algorithm can be used without changes with different PAs in different applications.

All the digital predistortion approaches mentioned above use adaptation of the predistorter in the time domain. Another approach is to use adaptation in the frequency domain (Stapleton & Costescu 1992, Laki & Kikkert 2012). The idea is to monitor the ACP generated by the PA. The results adjust the predistorter so as to minimise the ACP. That approach is different from the one used in this thesis, and therefore it is not considered any more in this thesis.

In the literature, there are also papers which consider timing errors in the feedback loop for predistortion. Li et al. (2009) have proposed a multilevel LUT with feedback loop delay compensation. Delay errors less than a typical sample interval are compensated and compared to the case without delay compensation, and significant performance improvements of mean square error and ACP are obtained. In a recent paper, feedback loop delay compensation has also been considered (Liu et al. 2012).

For the RoF link, there are three different types of compensation methods: optical, electro-optical, and electrical. In the optical method, the compensation is done using optical components in the optical domain, see e.g., (Lu et al. 2004, Lim et al. 2007). Electrical components and circuits are used in the electrical compensation methods (Fernando & Sesay 2002, Shen et al. 2010). The analogue and digital compensation techniques discussed above can be used for the compensation of nonlinear RoF links. In the electro-optical method, both optical and electrical components and methods are used (Ismail et al. 2007). It can be mentioned that both optical and electrical methods give a comparable performance, but the optical methods have a disadvantage of higher costs due to the need of additional optical components (Sadhwani & Jalali 2003). When centralising the compensation of RoF link nonlinearities in the central unit, postdistortion and predistortion can be used in the uplink (UL) and downlink (DL) directions, respectively (Hekkala et al. 2012).

When considering adaptive compensation of the DL RoF link, the feedback RoF link can distort the feedback signal in the same fashion as in the RoF link to be compensated (Fernando & Sesay 2002, Hekkala et al. 2012). The predistorter, or actually the predistorter training block, i.e., the postdistorter, should ideally see only the distortions it tries to compensate. Therefore, it can be assumed that the nonlinear feedback degrades the performance of the predistorter. In (Fernando & Sesay 2002), it has been mentioned that the UL RoF link could be used as the feedback RoF link. The UL RoF link has to be linearised prior to using the post-distorter and a known training signal. As an additional challenge in the compensation of the RoF link, there can be two nonlinear components connected in series, namely the RoF link itself and the power amplifier. It would be difficult to analyse the behaviour of these serial nonlinearities (Lasanen et al. 2008, Hekkala et al. 2012).

2.5 Envelope tracking amplifier

As already mentioned, the high efficiency of the ET PA is obtained by dynamically modifying the supply voltage by the envelope of the transmitted signal, see Figure 1.2. The idea is to obtain the PA with just sufficient supply voltage to get, at least almost, linear amplification at any particular point in time. In that way, the ET PA operates continuously close to its saturation area or even in the saturation (Raab et al. 2002, Kim et al. 2010). As can be seen in the figure, the ET PA has two inputs, the actual RF signal to be transmitted and the varying supply. To get correct operations of the ET PA, the two inputs have to be accurately time-aligned (Wang et al. 2005). Due to the changing supply voltage, the ET PA is, in practice, more nonlinear than the conventional PA (Sahu 2004).

The efficiency of the ET PA structure depends not only on the efficiency of the amplifier itself but also on the efficiency of the dynamic power supply. The bandwidth of the envelope is more than three times larger than the bandwidth of the RF signal to be transmitted (Cripps 2006); see also (Bello 1965). Therefore, very wideband supply modulators are needed and the efficiency of the power supply becomes even more important. To improve the efficiency, the bandwidth of the envelope signal can be reduced; see (Sahu 2004, Jeong et al. 2009, Gilabert & Montoro 2012). The bandwidth reduction distorts the signal, which needs to be compensated using, for example, the predistortion discussed above.

Cao et al. (2012) have proposed using a dual input modelling approach for the predistortion of the ET PA. Their approach is able to achieve maximisation of the efficiency and minimisation of the distortions simultaneously. The reduced envelope bandwidth technique can be applied to it, too. It also relaxes the sensitivity of the time misalignment between the two paths.

In the ET PA, it may be difficult to compensate the distortions due to the fact that the ET PA has very distinct characteristics in different amplitude regions. Zhu et al. (2008b) propose dividing the input signal into several sub-signals according to the ET PA characteristics. Each of these sub-signals is processed and predistorted separately using the piecewise Volterra series. Finally, to get the predistorted output signal, a recombination of the sub-signals is done.

In a recent paper, Yu & Zhu (2012) have proposed an interesting ET structure with predistortion in the MIMO transmitter; only one supply modulator is used for all the PAs in the different MIMO branches. Note that, in the conventional MIMO ET structure, each of the PAs has its own power supply. The common envelope, which modifies the single supply, is created by taking all the time a maximum of each individual envelope signal. This is needed to avoid possible saturation of a single PA. Additional distortions are introduced due to the fact that the envelope and RF signals in the PA no longer exactly match. However, the predistorter, which has also knowledge of the common envelope signal, has been proposed to compensate the distortions. By reducing the number of the supplies, the cost of the transmitter is significantly reduced.

Compensation of timing alignment error between the RF and envelope paths in the ET PA structure is considered in (Wang et al. 2005). The authors estimate the feedback delay via amplitude covariance between the feedback and baseband signal. Then, the delay between RF and envelope path is estimated by comparing the phases of the baseband and feedback signal. Some impairment, such as the amplitude-to-phase distortion of the PA, is ignored and the predistorter is assumed to be ideal in the study. In addition, the adaptive algorithm is not defined in detail. Wang et al. (2005) also compare the sensitivity of the EER and ET structures to timing errors between the RF and envelope paths. From the results, it can be seen that the required timing synchronisation accuracy is much smaller than the typical sample interval. However, the ET structure is less sensitive to these errors than the EER one (Wang et al. 2005, Kim et al. 2010).

3. Summary of the original papers

3.1 Overview of the papers

The contents of the original papers of this thesis fall into the general context of compensation of nonlinear transmitters using predistortion techniques. Papers I–IV study compensation of the RoF link. Paper III also considers PA compensation. In Paper V, the nonlinearities and time misalignments of the ET amplifier are compensated using predistortion techniques as well.

Papers I and III have been published in conference proceedings. Papers II, IV and V are journal articles. The papers include analysis, simulations, and measurements as shown in Table 3.1. Table 3.2 shows how the RoF link and ET amplifier case studies are related to the papers. In the following, the papers are shortly summarised, highlighting the key results. In addition, the roles and contributions of the author of the thesis are described in more detail.

Table 3.1. Research methods used in the original papers.

Paper	**I**	**II**	**III**	**IV**	**V**
Analysis		x		x	x
Simulations	x	x	x	x	x
Measurements				x	

Table 3.2. Relation of the original papers to the research studies.

Paper	**I**	**II**	**III**	**IV**	**V**
RoF link					
Architecture			x	x	
Algorithms	x	x	x	x	
PA included			x		
ET amplifier					
Architecture					x
Algorithms					x

3.2 Compensation of radio-over-fibre link

3.2.1 Paper I: Performance of adaptive algorithms for compensation of radio over fiber links

Paper I considers the performance of adaptive algorithms for the predistortion of the RoF link. It proposes and compares extended versions of two algorithms developed originally for the compensation of linear systems. The algorithms are the LMS and variable step size normalised LMS (VS NLMS) algorithms. The LMS methods are extended to also handle higher order nonlinear terms of the transmitted signal. In particular, the scaled step sizes of the LMS adaptation for the nonlinear polynomial predistorter are applied. The scaling is done based on the signal power of the corresponding nonlinear order of the feedback signal. It is noticed that scaling can be done off-line. Because of the scalable feature, the modified LMS algorithm converges much faster than the conventional LMS algorithm, as seen in Figure 3.1.

In addition, it is shown that steady state misadjustment can be reduced by decreasing the step size after the convergence of the algorithm. The complexity of the algorithms is also discussed. The RLS solution is used as a performance reference in the studies of Paper I.

In Paper I, the author had the main responsibility for developing the ideas of compensation algorithms studies and simulations. Mika Lasanen has supported the work and provided guidance as well as criticism.

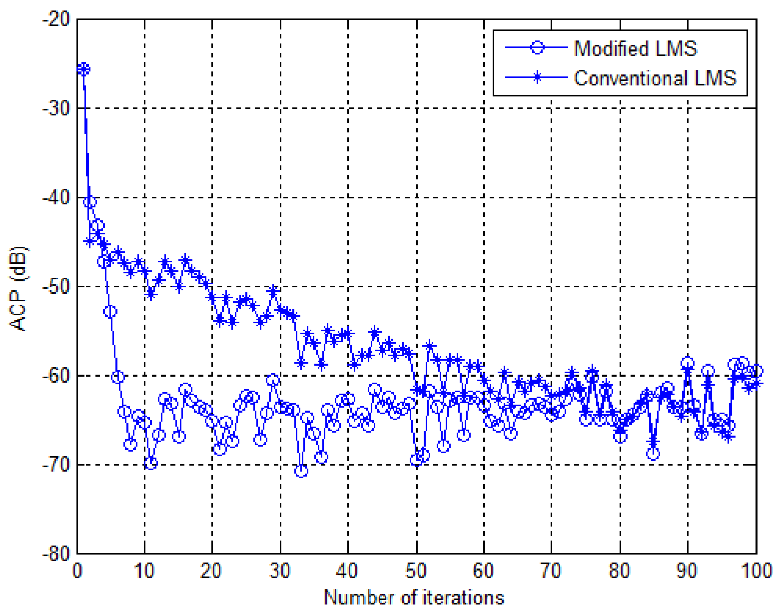


Figure 3.1. Achievable ACPs of the output signal after subsequent iterations using the conventional and modified LMS. Redrawn from Paper I. ©[2008] IEEE.

3.2.2 Paper II: Analysis of and compensation for non-ideal RoF links in DAS

Paper II continues the work of Paper I. The paper studies analysis and compensation of nonidealities introduced in the RoF links of a DAS system. The block diagram of the simplified system model is shown in Figure 3.2. In particular, a detailed discussion of the nonlinearities and delays stemming from the RoF link is provided and the compensation of the nonidealities is considered. In DASs, mobile terminals can communicate simultaneously with multiple remote antenna units. For that reason, the signal delays between the transmitter and receiver vary much more than in the conventional wireless communication systems. It is shown that in DASs, the delay effects need to be taken into account and compensated for as well. Otherwise, spectral efficiency decreases due to the required long cyclic prefixes in the OFDM systems or additional inter symbol interference is induced due to too short cyclic prefixes. Moreover, the in-band distortions due to the nonlinearities are not critical; remarkable degradations of the BER and EVM are observed only with large constellations of the modulation. On the other hand, out-of-band distortions are more significant. Using the predistortion technique presented in Paper I, a significant reduction in the in-band and out-of-band distortions is achieved. In the predistortion studies, the effects of the nonideal feedback are also included in the considerations. The problem of the nonideal feedback is studied in more detail in Paper III.

In Paper II, the author had the main responsibility for studying the effects of the nonlinearities on the EVM and spectral regrowth as well as the compensation of them. Mika Lasanen and Ilkka Harjula carried out bit error rate analyses. Luis Vieira, Nathan Gomes, and Anthony Nkansah contributed to the material related to the RoF link modelling. Steffen Bittner, Fabian Diehm, and Vincent Kotzsch studied delay effect analysis and compensation.

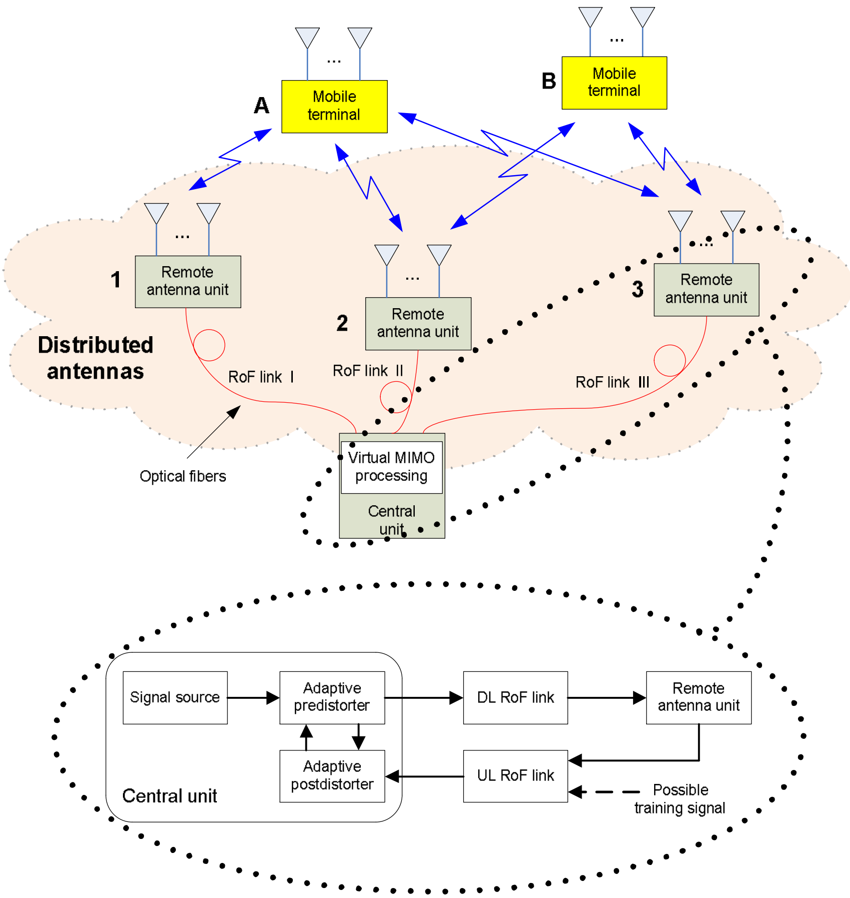


Figure 3.2. Simplified DAS and RoF link. Redrawn from Paper II. ©[2010] IEEE.

3.2.3 Paper III: Architectures for joint compensation of RoF and PA with nonideal feedback

Paper III continues the work of Paper I. The paper considers joint adaptive predistortion of a nonlinear RoF link and a PA connected in series. In particular, the architectures of the joint compensation of the RoF link and PA are studied. Two feedback connection options from the remote antenna unit are considered. More specifically, after a possible compensation of the feedback, the RoF link and PA are compensated in a consecutive manner, i.e., two feedback connections are used, namely after the RoF link and after the PA, respectively. In the other option, the RoF link and PA are compensated simultaneously, i.e., only one feedback connection is needed, namely after the PA. In addition, the effects of the nonideal feedback are taken into account. The block diagram of the system model showing detailed feedback connection is shown in Figure 3.3.

It is shown that the use of uncompensated feedback collapses the performance of the predistortion. The feedback can be compensated by the postdistortion, and thus almost the same performance as with the ideal feedback is achieved. Moreover, the best performance is achieved by doing the compensation in two consecutive phases.

In Paper III, the author developed the ideas of the compensation architecture and carried out simulations. Mika Lasanen supported the work at a general level. Luis Vieira, Nathan Gomes, and Anthony Nkansah provided the model of the RoF link.

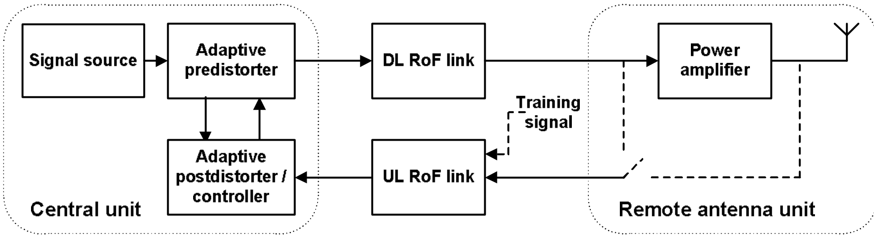


Figure 3.3. Block diagram of the system model showing detailed feedback connection. Redrawn from Paper III. ©[2010] IEEE.

3.2.4 Paper IV: Predistortion of radio over fiber links: algorithms, implementation, and measurements

Paper IV continues the works in Papers I, II, and III. The paper considers adaptive predistortion of the nonlinear RoF link. The details of the extension to the conventional LMS algorithm for the MP predistorter are provided. In addition, different algorithm combinations for the predistortion are studied. The use of DSP in the adaptation performed off-line makes it possible to change adaptation algorithms in a flexible manner. Moreover, the performance of the adaptive predistortion is verified by implementing the predistorter in an FPGA-based hardware platform and performing measurements over a real RoF link. In the measurements, the OFDM signal with the bandwidth of 6.25 MHz and sampling rate of 32 MHz is used. The signal is transmitted through the RoF link at an intermediate frequency (IF) of 50 MHz.

Paper IV finds that the nonlinearity is well compensated and the memory effects are considerably reduced by the proposed predistortion technique. In addition, both fast algorithm convergence and low algorithm complexity, i.e., energy savings, are achieved via the combined use of the RLS and LMS algorithms.

The measured EVMs for floating- and fixed-point predistorters and adaptation algorithms with different signal powers are shown in Table 3.3. As can be seen, almost the same performance is achieved using both the RLS and LMS algorithms. Moreover, using the fixed-point predistorter with a word length of 12 bits, as good performance as that obtained with the floating-point predistorter is achieved.

In addition, the spectra of the uncompensated and compensated signals are shown in Figure 3.4. As seen in the EVM tests, the performance of the fixed point predistorter with 8 bits is not good, whereas the predistorter having a word length of 12 bits achieves about 10 dB lower spectrum sidelopes than in the uncompensated case.

In Paper IV, the author introduced the extensions to the conventional LMS algorithm as well as the use of different algorithm combinations for the predistortion. In addition, the author verified the compensation performance by measurements. Mika Lasanen supported the algorithm-related work. Mikko Hiivala and Jari Perttu implemented the predistorter in hardware. The real RoF link used in the measurements was provided by Luis Vieira, Nathan Gomes, and Anthony Nkansah.

Table 3.3. Measured EVMs. Redrawn from Paper IV. ©[2012] IEEE.

Algorithm	RLS	RLS+LMS	LMS	RLS	RLS+LMS	LMS
Signal power at laser input (dBm)		8			5	
Uncompensated EVM (%)		4.6			3.6	
Floating point PD EVM (%)	0.9	1.0	1.0	0.7	0.6	0.7
Fixed point PD (12 bit) EVM (%)	0.9	0.9	1.1	0.7	0.6	0.8
Fixed point PD (10 bit) EVM (%)	1.0	1.0	1.2	0.8	0.8	0.9
Fixed point PD (8 bit) EVM (%)	2.6	2.3	2.1	2.3	1.9	2.1

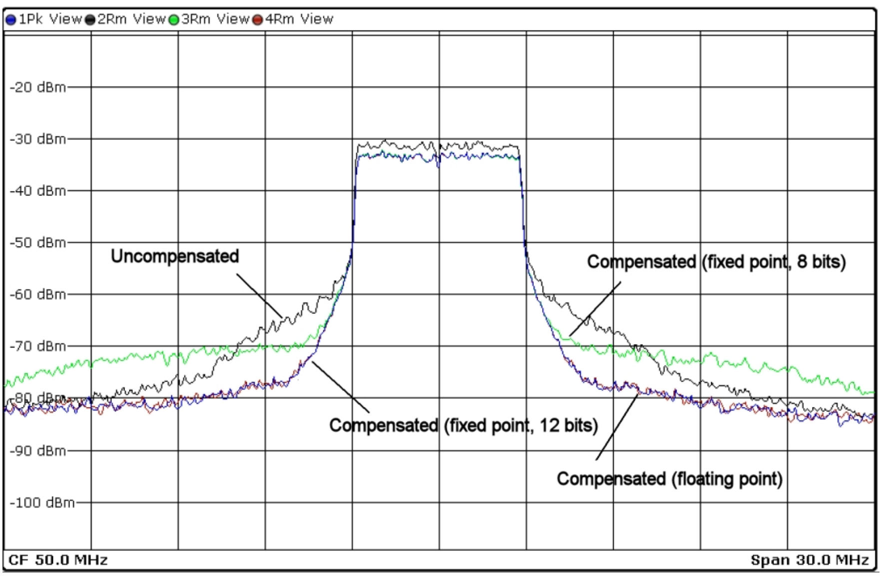


Figure 3.4. Spectra of uncompensated and compensated signals. Redrawn from Paper IV. ©[2012] IEEE.

3.3 Compensation of envelope tracking amplifier

3.3.1 Paper V: Novel digital compensation approaches for envelope tracking amplifiers

Paper V considers compensation of the ET amplifier. In particular, a new predistortion architecture for the ET amplifiers is proposed. The block diagram of the simplified system model is show in Figure 3.5. The architecture can be applied to a wide class of ET amplifiers. This architecture is compared to the conventional architecture in the literature. The performances of the optimal and adaptive predistorters are evaluated. The complexity of the predistorters is also discussed.

In addition, a time misalignment compensation method presented earlier in the literature is further developed. Moreover, a new time misalignment compensation method is proposed. In the presence of optimal and adaptive predistorters, the performances of the time misalignment compensation methods are demonstrated for the linear filters and ET amplifier.

Using the proposed architecture, much better performance is achieved compared to the previously presented one. It is also shown that the time misalignment deteriorates significantly the nonlinearity of the ET amplifier. Using the proposed methods, very accurate timing estimates are achieved.

In Paper V, the author was responsible for proposing a new general predistorter approach. Moreover, the author analysed and compared the new approach against the conventional architecture. The author studied its performance by developing recursive solutions of time misalignment compensation with the adaptive predistorter, and evaluating through simulations the performance of the time misalignment compensation methods. This work was carried out with the support of Mika Lasanen and Adrian Kotelba. Pertti Järvensivu and Aarne Mämmelä provided scientific support and criticism to the work.

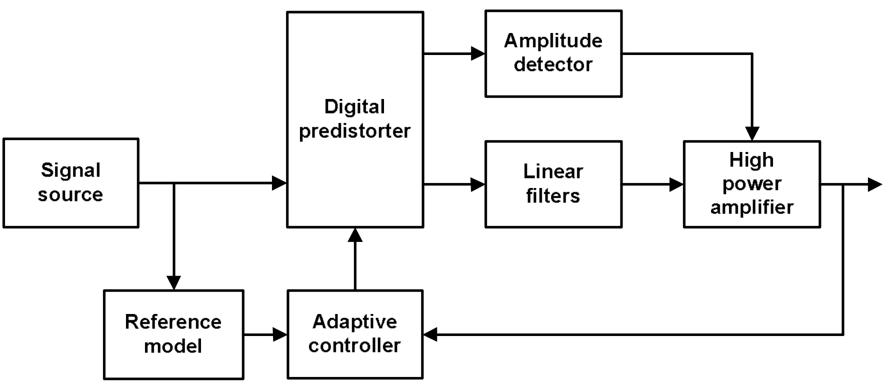


Figure 3.5. Block diagram of the simplified system model. Redrawn from Paper V. ©[2012] Springer.

4. Discussion

4.1 Main findings

It is a well-known fact that nonlinearities have to be taken into account when designing wireless communication systems. Nonlinearities cause in-band and out-of-band distortions to the transmitted signal. For example, the spectral regrowth reduces spectral efficiency because of the need of larger guard bands or reduces energy efficiency via the needed larger back-off of the PA. In-band distortions limit system capacity and may require more complex receiver algorithms. In that way, nonlinearity has a significant impact on the users, operators, and manufacturers.

Nonlinearities can be compensated using the low complex predistortion schemes proposed in this thesis. It has been shown that the in-band distortions are not critical; only with a large constellation of the modulations remarkable performance degradations have been noticed. However, noticeable improvements of the EVM have been achieved, making it possible to use larger constellations. On the other hand, the out-of-band distortions are more significant. Considering the ACPs, the distortions have been significantly reduced.

The low complex LMS algorithm can be used for adaptive compensation of the nonlinear transmitter even if it has a slower convergence rate than the RLS solution. In this thesis, extensions have been proposed for the LMS algorithm. The modifications are based on the scaling of the step sizes according to the signal power of the corresponding nonlinear order of the signal. Compared to the conventional LMS algorithm, a much faster convergence has been achieved using the modified LMS algorithm.

Due to the flexible use of DSP, a combination of the LMS and RLS algorithms can be used for implementing the adaptation algorithms. Due to the assumed slow changes in the nonlinear characteristics of the nonlinear components, the adaptation can be done off-line. Both fast algorithm convergence and low algorithmic complexity, i.e., energy savings, are achieved via a combined use of the RLS and LMS algorithms. On the other hand, the steady-state misadjustment of the LMS algorithm has been reduced by turning the tracking mode on, i.e., decreasing the step size after the convergence of the algorithm.

It has been shown that the proposed predistortion concept can be practically implemented in hardware and therefore it can be used in real products. Moreover, using the fixed-point predistorter with a word length of 12 bits, an equally good performance as with the floating-point predistorter has been achieved. Using a word length of 10 bits results in a small performance degradation.

In the studies on the RoF link compensation, it has been found that the nonideal feedback has to be taken into account. Without the compensation, the performance collapses. As has been demonstrated in this thesis, the nonideal feedback can be compensated using postdistortion and a known training signal. The approach requires an additional training signal from the remote antenna unit.

When compensating two nonlinear components connected in series, it is important to consider the compensation architecture. In this thesis, two feedback connection options from the remote antenna unit have been considered. The results indicate that it is reasonable to jointly compensate the RoF link and PA in a consecutive manner.

A general approach for the predistortion of the ET amplifier has been proposed, and its performance has been demonstrated with optimal and adaptive predistorters. It has also been shown that the time misalignment deteriorates significantly the nonlinearity of the ET amplifier. Using the proposed time misalignment compensation methods, very accurate timing estimates have been achieved, making it possible to attain linear amplification.

4.2 Limitations and recommendations for future work

There are some limitations associated with the studies presented here. Many of these could be assumed as topics for future work. Therefore, recommendations for the further work are also discussed here.

When compensating a nonlinear transmitter, it is well known that the impact of, for example, linear filters in the feedback may destroy the effect of adaptive compensation. In the studies on the ET amplifier compensation, the feedback has been assumed to be ideal. Actually, considerations of the nonideal feedback and its effects on the compensation of the transmitter could be a topic for future work. In the studies on the RoF link compensation, the feedback has also been assumed to be ideal, except for the RoF link part of the feedback, which has been discussed in Paper IV. The delays in the feedback are not critical. These can be easily taken into account, as shown in Paper V.

Another limitation is the lack of knowledge about practical systems. To extend the studies towards more realistic systems, more information about real systems and their models should be obtained. There are number of questions to be studied. For example, from the adaptive algorithms point of view, how fast the adaptation should be in practice? Is the speed of the LMS algorithm convergence fast enough? Is the complexity of the RLS solution prohibitive or not? What is the role of the power control in the operation of the predistortion scheme? On the other hand, it is difficult to study and model the nonidealities without the knowledge of the real equipment.

Again considering the work on the ET amplifier compensation, the model of the amplifier does not include memory effects. Against the current trends towards larger and larger signal bandwidths, the model is becoming somewhat outdated due to its memoryless nature. In addition, phase noise, I/Q imbalance, and DC offset have been ignored in the study. No realistic considerations have been done on terms of the envelope signal of the ET amplifier. It has been assumed to be ideal, which means that it has a very high bandwidth. In practice, the bandwidth is limited, i.e., it is no longer an accurate replica of the signal envelope. This is again worth of further study. The ET amplifier should be modelled with memory and the challenges of the envelope signal should be considered. Taking into account the energy consumption of the entire transmitter, it is even more important because of the processing of the envelope signal consumes significant amount of the total energy consumption of the ET amplifier.

In Paper IV, the measurements have been done with the RoF link operating at IF. Operation at higher frequencies, which is often the case for wireless communication systems, has been expected to create more severe nonlinearities. In addition, fibre distortion creates more distortions then, too. Again, this is a relevant topic for further studies using more realistic and accurate models. Perhaps, more complex compensation methods will be needed especially if there are several nonlinear components connected in series, see also (Lasanen et al. 2008). In addition, as already discussed in Paper III, providing long feedback over the RoF network is costly and requires a lot of resources, i.e. RoF channels in the fibres. Further considerations on the compensation architecture for the RoF link would be needed.

Normally, the signals of several users are multiplexed together into a single RoF link. However, only single-user scenarios have been used in this thesis. Therefore, the interference between different signals due to the nonlinearities of the RoF link has not been considered. In addition, all the models used in this thesis are time invariant. Therefore, the characteristics of the models do not change in time as it is the case with real products or components.

Extensive comparisons with other predistortion concepts are missing. Only in Papers I and V, some comparisons with the adaptive algorithms and the state-of-the-art compensation structure, respectively, have been done. In the future, it could be reasonable to compare the MP approach with, for example, the LUT-based predistortion. Moreover, it is important to study the compensation of the nonlinear transmitter taking into account the energy consumption of the entire transmitter including, among others, feedback, needed oversampling, and signal processing.

One clear trend in wireless communication is going towards smaller cells. It means an increasing number of base stations and lower transmission power levels. This in turn means cheaper and lower cost PAs. Therefore, the energy efficiency of the PA is not so critical any more. However, out-of-band and in-band distortions may still need to be compensated. In addition, larger cells will be needed alongside with the small cells also in the future.

Even though some statistical simulations of, for example, the EVMs or ACPs in Papers III and V, respectively, have been shown, more analysis should be done in the future. The convergence of the predistorter should be studied in more detail from the statistical study point of view. This is also related to the stability considerations of the predistorter. One additional topic for further work could be to study the signal quality if the predistorter does not converge.

5. Conclusion

This thesis has studied the compensation of the nonlinear distortions introduced in the transmitters of wireless communication systems. In particular, adaptive predistortion of the ET amplifier and the RoF link has been considered. Developing compensation algorithms and architectures for predistortion have been the main goal of this thesis.

This thesis has reviewed the relevant literature on the compensation of nonlinear transmitters. Highly efficient transmitters have been briefly discussed, and one of them, namely the ET amplifier, has been considered in more detail. As an important part of compensation studies, PA models have been introduced following the discussions about compensation architectures and algorithms. Again, one of the compensation methods, predistortion, has been studied in more detail.

By providing low attenuation and enormous bandwidth, the RoF technology enables using cost-efficient and energy-efficient DASs. Using highly efficient PA structures, such as ET amplifiers, the energy efficiency of the transmitters is increased. Unfortunately, the RoF links as well as the ET amplifiers are inherently nonlinear. The results of this thesis indicate that these nonlinearities have to be taken into account when designing wireless communication systems. The nonlinearities can be compensated using the low complex adaptive predistortion techniques proposed in this thesis.

A general architecture for predistortion of the ET amplifier has been proposed. Using the architecture, the performance of predistortion has been demonstrated. In addition, new time misalignment compensation methods have been proposed and their performances have been studied.

For the compensation of the RoF link, an extension to the conventional LMS algorithm for MP-based predistortion has been presented. In addition, different combinations of adaptive algorithms for predistortion have been considered. From the compensation architecture point of view, a joint compensation of the RoF link and PA connected in series in the presence of nonlinear feedback has been studied. Finally, the feasibility of the adaptive predistortion concept has been demonstrated by the measurements on a real system.

The results presented in this thesis can be applied to any wireless communications systems. The performance studies demonstrate that distortions of the RoF link and the ET amplifier can be considerably diminished using a low-complexity design. In order to further improve the linearity and energy-efficiency, the proposed predistortion techniques can be implemented together with other techniques, such as the PAPR reduction methods.

References

3GPP TS36.104. 2013. 3rd generation partnership project; technical specification group radio access network; evolved universal terrestrial radio access (E-UTRA); base station (BS) radio transmission and reception (Release 12). Version 12.1.0.

Afsardoost S., Eriksson T. & Fager C. 2012. Digital predistortion using a vector-switched model. IEEE Transactions on Microwave Theory and Techniques, Vol. 60, No. 4, pp. 1166–1174. ISSN: 0018-9480.

Al-Raweshidy H. & Komaki S. Eds. 2002. Radio over fiber technologies for mobile communications networks. Norwood MA: Artech House. ISBN: 1-58053-148-2.

Anttila L., Handel P. & Valkama M. 2010. Joint mitigation of power amplifier and I/Q modulator impairments in broadband direct-conversion transmitters. IEEE Transactions on Microwave Theory and Techniques, Vol. 58, No. 4, pp. 730–739. ISSN: 0018-9480.

Auer G., Giannini V., Desset C., Godor I., Skillermark P., Olsson M., Imran M. A., Sabella D., Gonzalez M. J., Blume O. & Fehske A. 2011. How much energy is needed to run a wireless network? IEEE Wireless Communications, Vol. 18, No. 5, pp. 40–49. ISSN: 1536-1284.

Bassam S. A., Helaoui M. & Ghannouchi F. M. 2009. Crossover digital predistorter for the compensation of crosstalk and nonlinearity in MIMO transmitters. IEEE Transactions on Microwave Theory and Techniques, Vol. 57, No. 5, pp. 1119–1128. ISSN: 0018-9480.

Bateman A. 1992. The combined analogue locked loop universal modulator (CALLUM). In Proceedings of 42nd IEEE Vehicular Technology Conference (VTC), 1992, pp. 759–763. ISBN: 1090-3038.

Bello P. 1965. On the rms bandwidth of nonlinearly envelope detected narrow-band Gaussian noise. IEEE Transactions on Information Theory, Vol. 11, No. 2, pp. 236–239. ISSN: 0018-9448.

Black H. S. 1934. Stabilized feed-back amplifiers. Transactions of the American Institute of Electrical Engineers, Vol. 53, No. 1, pp. 114–120.

Boumaiza S. & Ghannouchi F. M. 2003. Thermal memory effects modeling and compensation in RF power amplifiers and predistortion linearizers. IEEE

Transactions on Microwave Theory and Techniques, Vol. 51, No. 12, pp. 2427–2433. ISSN: 0018-9480.

Cao H., Nemati H. M., Tehrani A. S., Eriksson T. & Fager C. 2012. Digital predistortion for high efficiency power amplifier architectures using a dual-input modeling approach, IEEE Transactions on Microwave Theory and Techniques, Vol. 60, No. 2, pp. 361–36. ISSN: 0018-9480.

Celka C., Bershad N. J. & Vesin J.-M. 2001. Stochastic gradient identification of polynomial Wiener systems: Analysis and application. IEEE Transactions on Signal Processing, Vol. 49, No. 2, pp. 301–309. ISSN: 1053-587X.

Chen H.-H., Lin C.-H., Huang P.-C., & Chen J.-T. 2006. Joint polynomial and look-up-table predistortion power amplifier linearization. IEEE Transactions on Circuits and Systems II: Express Briefs, Vol. 53, No. 8, pp. 612–616. ISSN: 1549-7747.

Chen S. & Yuan J. S. 2011. Adaptive gate bias for power amplifier temperature compensation. IEEE Transactions on Device and Materials Reliability, Vol. 11, No. 3, pp. 442–449. ISSN: 1530-4388.

Cheong M. Y., Werner S., Bruno M., Figueroa J., Cousseau J. & Wichman R. 2012. Adaptive piecewise linear predistorters for nonlinear power amplifiers with memory. IEEE Transactions on Circuit and Systems-I: Regular papers, Vol. 59, No. 7, pp. 1–14. ISSN: 1549-8328.

Chireix H. 1935. High power outphasing modulation. Proceedings of the Institute of Radio Engineers, Vol. 23, No. 11, pp. 1370–1392. ISSN: 0018-9219.

Choi S., Jeong E.-R. & Lee Y. H. 2009. Adaptive predistortion with direct learning based on piecewise linear approximation of amplifier nonlinearity. IEEE Journal on Selected Topics in Signal Processing, Vol. 3, No. 3, pp. 397–404. ISSN: 1932-4553.

Claasen T. A. C. M. & Mecklenbräuker W. F. G. 1985. Adaptive techniques for signal processing in communications. IEEE Communications Magazine, Vol. 23, No. 11, pp. 8–19. ISSN: 0163-6804.

Clark C. J., Chrisikos G., Muha M. S., Moulthrop A. A. & Silva C. P. 1998. Time-domain envelope measurement technique with application to wideband power amplifier modelling. IEEE Transactions on Microwave Theory and Techniques, Vol. 46, No. 12, pp. 2531–2540. ISSN: 0018-9480.

Correia L. M., Zeller D., Blume O., Ferling D., Jading Y., Gódor I., Auer G. & Van Der Perre L. 2010. Challenges and enabling technologies for energy aware mobile radio networks. IEEE Communications Magazine, Vol. 48, No. 11, pp. 66–72. ISSN: 0163-6804.

Cox D. 1974. Linear amplification with nonlinear components. IEEE Transactions on Communications, Vol. 22, No. 12, pp. 1942–1945. ISSN: 0090-6778.

Cox D. 1975. Linear amplification by sampling techniques: A new application for delta coders. IEEE Transactions on Communications, Vol. 23, No. 8, pp. 793–798. ISSN: 0090-6778.

Cox III C. H. 2004. Analog optical links: theory and practice. Cambridge, UK: Cambridge University Press. ISBN: 0-521-62163-1.

Cripps S. C. 2006. RF power amplifiers for wireless communications. 2nd edition. Norwood MA: Artech House. ISBN: 1-59693-018-7.

Ding L., Zhou G. T., Morgan D. R., Ma Z., Kenney J. S., Kim J. & Giardina C. R. 2004. A robust digital baseband predistorter constructed using memory polynomials. IEEE Transactions on Communications, Vol. 52, No. 1, pp. 159–165. ISSN: 0090-6778.

Ding L. & Zhou G. T. 2004. Effects of even-order nonlinear terms on power amplifier modeling and predistortion linearization. IEEE Transactions on Vehicular Technology, Vol. 53, No. 1, pp. 156–162, ISSN: 0018-9545.

Doherty W. H. 1936. A new high efficiency power amplifier for modulated waves. Proceedings of IRE, Vol. 24, No. 9, pp. 1163–1182. ISSN: 0096-8390.

Eron M., Kim B., Raab F., Caverly R. & Staudinger J. 2011. The head of the class. IEEE Microwave Magazine, Vol. 12, No. 7, pp. S16–S33. ISSN: 1527-3342.

Eun C. & Powers E. J. 1997. A new Volterra predistorter based on the indirect learning architecture. IEEE Transactions on Signal Processing, Vol. 45, No. 1, pp. 223–227. ISSN: 1053-587X.

Fernando X. N. & Sesay A. B. 2002. Adaptive asymmetric linearization of radio over fiber links for wireless access. IEEE Transactions on Vehicular Technology, Vol. 51, No. 6, pp. 1576–1586. ISSN: 0018-9545.

Fettweis G., Löhning M., Petrovic D., Windisch M., Zillmann P. & Rave W. 2007. Dirty RF: a new paradigm. International Journal of Wireless Information Networks, Vol. 14, No. 2, pp. 133–148. ISSN: 1068-9605.

Ghannouchi F. M. & Hammi O. 2009. Behavioral modeling and predistortion. IEEE Microwave Magazine, Vol. 10, No. 7, pp. 52–64. ISSN: 1527-3342.

Ghorbani A. & Sheikhan M. 1991. The effects of solid state power amplifier (SSPA) nonlinearities on M-PSK and M-QAM signal transmission. Proceedings of 6th International Conference on Digital Processing of Signals in Communications, Loughborough, UK, September, pp. 193–197. ISBN: 0-85296-522-2.

Gilabert P. L. & Montoro G. 2012. Look-up table implementation of a slow envelope dependent digital predistorter for envelope tracking power amplifiers. IEEE Microwave and Wireless Components Letters, Vol. 22, No. 2, pp. 97–99. ISSN: 1531-1309.

Gomes N. J., Monteiro P. P. & Gameiro A. (ed.) 2012. Next generation wireless communications using radio over fiber. West Sussex, United Kingdom: John Wiley & Sons. ISBN: 978-1-119-95339-5.

Gregorio F. H. 2007. Analysis and compensation of nonlinear power amplifier effects in multi-antenna OFDM systems. Ph.D. dissertation, Helsinki University of Technology, Espoo, Finland. ISBN: 978-951-22-9001-7.

Gregorio F., Cousseau C., Werner S., Riihonen T. & Wichman R. 2011. Power amplifier linearization technique with IQ imbalance and crosstalk compensation for broadband MIMO-OFDM transmitters. EURASIP Journal on Advances in Signal Processing, 2011:19. ISSN: 1687-6180.

Hammi O., Younes M. & Ghannouchi F. M. 2010. Metrics and methods for benchmarking of RF transmitter behavioral models with application to the development of a hybrid memory polynomial model. IEEE Transactions on Broadcasting, Vol. 56, No. 3, pp. 350–357. ISSN: 0018-9316.

Han S. H., & Lee J. H. 2005. An overview of peak-to-average power ratio reduction techniques for multicarrier transmission. IEEE Wireless Communications, Vol. 12, No. 2, pp. 56–65. ISSN: 1536-1284.

Harvey C., Symington I. & Kirsten D. 1991. Cordless communications utilising radio over fibre techniques for the local loop. Proceedings of IEEE International Conference on Communications, Denver, US, June, pp. 1171–1175. ISBN: 0-7803-0006-8.

Haykin S. 2002. Adaptive Filter Theory. 4th edition. Upper Saddle River, NJ: Prentice Hall. ISBN: 0-13-090123-1.

Hekkala A., Lasanen M., & Kotelba A. 2008a. Adaptive time misalignment compensation in envelope tracking amplifiers. In Proceedings of IEEE International Symposium on Spread Spectrum Technologies and Applications (ISSSTA), Aug. 2008. ISBN: 978-1-4244-2203-6.

Hekkala A., Lasanen M., & Kotelba A. 2008b. Compensation of linear and nonlinear distortions in envelope tracking amplifier. In Proceedings of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Sep. 2008. ISBN: 978-1-4244-2643-0.

Hekkala A., Perttu J., Lasanen M., Vieira L. C. & Gomes N. J. 2010. Predistortion study of radio over fibre link, in Proceedings of Future Network & Mobile Summit, June 2010. ISBN: 978-1-905824-16-8.

Hekkala A., Lasanen M., Hiivala M, Vieira L. C., Gomes N. J., Kotzsch V. & Fettweis G. 2012. Compensation of impairments in the radio over fiber infrastructure. In: Gomes N. J., Monteiro P. P. & Gameiro A. (ed.) Next generation wireless communications using radio over fiber. West Sussex, United Kingdom: John Wiley & Sons, pp. 211–246. ISBN: 978-1-119-95339-5.

Holma H. & Toskala A. 2011. LTE for UMTS: evolution to LTE-advanced. John Wiley & Sons. ISBN: 978-0-470-66000-3.

Ismail T., Liu C.-P., Mitchell J. E. & Seeds A. J. 2007. High-dynamic-range wireless-over-fiber link using feedforward linearization. Journal of Lightwave Technology, Vol. 25, No. 11, pp. 3274–3282. ISSN: 0733-8724.

Jeong J., Kimball D. F., Kwak M., Hsia C., Draxler P. & Asbeck P. M. 2009. Wideband envelope tracking power amplifiers with reduced bandwidth power supply waveforms and adaptive digital predistortion techniques. IEEE Transactions on Microwave Theory and Techniques, Vol. 57, No. 12, pp. 3307–3314. ISSN: 0018-9480.

Jeruchim M. C., Balaban P. & Shanmugan K. S. 2000. Simulation of communication systems: modeling, methology, and techniques, 2nd ed. New York: Kluwer Academic/Plenum Publishers. ISBN: 0-306-43989-1.

Jiang H. & Wilford P. A. 2010. Digital predistortion for power amplifiers using separable functions. IEEE Transactions on Signal Processing, Vol. 58, No. 8, pp. 4121–4130. ISSN: 1053-587X.

Jiang T. & Wu Y. 2008. An overview: peak-to-average power ratio reduction techniques for OFDM signals. IEEE Transactions on Broadcasting, Vol. 54, No. 2, pp. 257–268. ISSN: 0018-9316.

Kahn L. R. 1952. Single-sideband transmission by envelope elimination and restoration. Proceedings of IRE, Vol. 40, No. 7, pp. 803–806. ISSN: 0096-8390.

Kang H. W., Cho Y. S. & Youn D. H. 1999. On compensating nonlinear distortions of an OFDM system using an efficient adaptive predistorter, IEEE Transactions on Communications, Vol. 47, No. 4, pp. 522–526. ISSN: 0090-6778.

Karam G. & Sari H. 1991. A data predistortion technique with memory for QAM radio systems. IEEE Transactions on Communications, Vol. 39, No. 2, pp. 336–344. ISSN: 0090-6778.

Katz A. 2001. Linearization: reducing distortion in power amplifiers, IEEE Microwave Magazine, Vol. 2, No. 4, pp. 37–49. ISSN: 1527-3342.

Kenington P. B. 2000. High-linearity RF amplifier design. Norwood MA: Artech House. ISBN: 1-58053-143-1.

Kenington P. B. 2002. Linearized transmitters: An enabling technology for software defined radio. IEEE Communications Magazine, Vol. 40, No. 2, pp. 156–162. ISSN: 0163-6804.

Kim J., Woo Y. Y., Moon J. & Kim B. 2008. A new wideband adaptive digital predistortion technique employing feedback linearization. IEEE Transactions on Microwave Theory and Techniques, Vol. 56, No. 2, pp. 385–392. ISSN: 0018-9480.

Kim B., Moon J. & Kim I. 2010. Efficiently amplified. IEEE Microwave Magazine, Vol. 11, No. 5, pp. 87–100. ISSN: 1527-3342.

Kim J. & Konstantinou K. 2001. Digital predistortion of wideband signals based on power amplifier model with memory, Electronics Letters, Vol. 37, No. 23, pp. 1417–1418. ISSN: 0013-5194.

Kim W.-J., Cho K.-J., Stapleton S. P. & Kim J.-H. 2006. Piecewise preequalized linearization of the wireless transmitter with a Doherty amplifier. IEEE Transactions of Microwave Theory and Techniques, Vol. 54, No. 9, pp. 3469–3478. ISSN: 0018-9480.

Kotelba A., Hekkala A. & Lasanen M. 2008. Compensation of time misalignment between input signals in envelope-tracking amplifiers. In Proceedings of

IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Sep. 2008. ISBN: 978-1-4244-2643-0.

Ku H. & Kenney J. S. 2003. Behavioral modeling of nonlinear RF power amplifiers considering memory effects. IEEE Transactions on Microwave Theory and Techniques, Vol. 51, No. 12, pp. 2495–2504. ISSN: 0018-9480.

Laki B. D. & Kikkert C. J. 2012. Adaptive digital predistortion for wideband high crest factor applications based on the WACP optimization objective: a conceptual overview. IEEE Transactions on Broadcasting, Vol. 58, No. 4, pp. 609–618. ISSN: 0018-9316.

Lasanen M., Kotelba A., Hekkala A., Järvensivu P. & Mämmelä A. 2008. Adaptive predistortion architecture for nonideal radio transmitter. In Proceedings of IEEE Vehicular Technology Conference (VTC-Spring), May 2008. ISBN: 978-1-4244-1644-8.

Lavrador P. M., Cunha T. R., Cabral P. M. & Pedro J. C. 2010. The linearity-efficiency compromise. IEEE Microwave Magazine, Vol. 11, No. 5, pp. 44–58. ISSN: 1527-3342.

Lee J., Kim Y., Lee H., Ng B. L., Mazzarese D., Liu J., Xiao W. & Zhou, Y. 2012. Coordinated multipoint transmission and reception in LTE-advanced systems. IEEE Communications Magazine, Vol. 50, No. 11, pp. 44–50. ISSN: 0163-6804.

Lee Y. S., Lee M. W. & Jeong Y. H. 2009. A wideband analog predistortion power amplifier with multi-branch nonlinear path for memory-effect compensation. IEEE Microwave and Wireless Components Letters, Vol. 19, No. 7, pp. 476–478. ISSN: 1531-1309.

Li; H., Kwon D. H., Chen D. & Chiu Y. 2009. A fast digital predistortion algorithm for radio-frequency power amplifier linearization with loop delay compensation. IEEE Journal of Selected Topics in Signal Processing, Vol. 3, No. 3, pp. 374–383. ISSN: 1932-4553.

Lim C., Nirmalathas A., Lee K. L., Novak D. & Waterhouse R. 2007. Intermodulation distortion improvement for fiber–radio applications incorporating OSSB+C modulation in an optical integrated-access environment. Journal of Lightwave Technology, Vol. 25, No. 6, pp. 1602–1612. ISSN: 0733-8724.

Liu Y.-J., Lu B., Cao T., Zhou B.-H., Zhou J. & Liu Y.-N. 2012. On the robustness of look-up table digital predistortion in the presence of loop delay error, IEEE Transactions on Circuits and Systems I: Regular Papers, Vol. 59, No. 10, pp. 2432–2442. ISSN: 1549-8328.

Lu H.-H., Lai P.-C. & Tsai W.-S. 2004. Radio-on-multimode fiber systems based on VCSELs and external light injection technique. IEEE Photonics Technology Letters, Vol. 16, No. 4, pp. 1215–1217. ISSN: 1041-1135.

Ma Y., He S., Akaiwa Y. & Yamao Y. 2011. An open-loop digital predistorter based on memory polynomial inverses for linearization of RF power amplifier. International Journal of RF and Microwave Computer-Aided Engineering, Vol. 21, No. 5, pp. 589–595. ISSN: 1099-047X.

Macdonald J. 1959. Nonlinear distortion reduction by complementary distortion. IRE Transactions on Audio, Vol. 5, pp. 128–133. ISSN: 0096-1981.

Moon H. & Sedaghat R. 2006. FPGA-based adaptive digital predistortion for radio-over-fiber links. Microprocessors and Microsystems, Vol. 30, No. 3, pp. 145–154. ISSN 0141-9331.

Morgan D. R., Ma Z., Kim J., Zierdt M. G. & Pastalan J. 2006. A generalized memory polynomial model for digital predistortion of RF power amplifier. IEEE Transactions on Signal Processing, Vol. 54, No. 10, pp. 3852–3860. ISSN: 1053-587X.

Mämmelä A. 2006. Commutation in linear and nonlinear systems. Frequenz. Vol. 60, May/June, pp. 92–94. ISSN: 2191-6349.

Nader C., Landin P. N., Van Moer W., Bjorsell N. & Handel P. 2011. Performance evaluation of peak-to-average power ratio reduction and digital pre-distortion for OFDM based systems, IEEE Transactions on Microwave Theory and Techniques, Vol. 59, No. 12, pp. 3504–3511. ISSN: 0018-9480.

Nielsen M. & Larsen T. 2007. A transmitter architecture based on delta–sigma modulation and switch-mode power amplification. IEEE Transactions on Circuits and Systems II: Express Briefs, Vol. 54, No. 8, pp. 735–739. ISSN: 1549-7747.

Paaso H. & Mämmelä A. 2008. Comparison of direct learning and indirect learning predistortion architectures. Proceedings of IEEE International Symposium on Wireless Communication Systems, 21–24 October 2008, pp. 309–313. ISBN: 978-1-4244-2488-7.

Pedro J. C. & Maas S. A. 2005. A comparative overview of microwave and wireless power-amplifier behavioral modeling approaches. IEEE Transactions on Microwave Theory and Techniques, Vol. 53, No. 4, pp. 1150–1163. ISSN: 0018-9480.

Proakis J. G. 1995. Digital Communications. New York: McGraw-Hill. ISBN: 0-07-051726-6.

Psaltis D., Sideris A. & Yamamura A. A. 1988. A multilayered neural network controller. IEEE Control Systems Magazine, Vol. 8, No. 2, pp. 17–21. ISSN: 0272-1708.

Raab F. H. 1975. High efficiency amplification techniques. IEEE Circuits and Systems, Vol. 7, No. 10, pp. 3–11. ISSN:

Raab F. H., Asbeck P., Cripps S., Kenington P. B., Popovic Z. B., Pothecary N., Sevic J. F. & Sokal N. O. 2002. Power amplifiers and transmitters for RF and microwave. IEEE Transactions on Microwave Theory and Techniques, Vol. 50, No. 3, pp. 814–826. ISSN: 0018-9480.

Raich R., Hua Q. & Zhou G. T. 2004. Orthogonal polynomials for power amplifier modeling and predistorter design. IEEE Transactions on Vehicular Technology, Vol. 53, No. 5, pp. 1468–1479. ISSN: 0018-9545.

Rawat M., Ghannouchi F. M. & Rawat K. 2012. Three-layered biased memory polynomial for dynamic modeling and predistortion of transmitters with memory. IEEE Transactions on Circuits and Systems I: Regular Papers, Vol. 60, No. 3, pp. 768–777. ISSN: 1549-8328.

Roselli L., Borgioni V., Zepparelli F., Ambrosi F., Comez M., Faccin P. & Casini A. 2003. Analog laser predistortion for multiservice radio-over-fiber systems. Journal of Lightwave Technology, Vol. 21, No. 5, pp. 1211–1223. ISSN: 0733-8724.

Sadhwani R. & Jalali B. 2003. Adaptive CMOS predistortion linearizer for fiber-optic links. Journal of Lightwave Technology, Vol. 21, No. 12, pp. 3180–3193. ISSN: 0733-8724.

Sahu B. 2004. Integrated, dynamically adaptive supplies for linear RF power amplifiers in portable applications. Ph.D. dissertation, Department of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA.

Saleh A. A. M. 1981. Frequency-independent and frequency-dependent nonlinear models of TWT amplifiers. IEEE Transactions on Communications, Vol. 29, No. 11, pp. 1715–1720. ISSN: 0090-6778.

Schetzen M. 1976. Theory of pth-order inverses of nonlinear systems. IEEE Transactions on Circuits and Systems, Vol. 23, No. 5, pp. 285–291. ISSN: 0098-4094.

Schetzen M. 1980. The Volterra and Wiener theories of nonlinear systems. Wiley. ISBN: 978-0-471-04455-0.

Seidel H. 1971. A feedforward experiment applied to an L-4 carrier system amplifier. IEEE Transactions on Communication Technology, Vol. 19, No. 3, pp. 320–325. ISSN: 0018-9332.

Shah A. R. & Jalali B. 2005. Adaptive equalisation for broadband predistortion linearisation of optical transmitters. IEE Proceedings – Optoelectronics, Vol. 152, No. 1, pp. 16–32. ISSN: 1350-2433.

Shahed A., Burglechner S., Gokceoglu A. H., Valkama M. & Springer A. 2012. Implementation and performance of DSP-oriented feedforward power amplifier linearizer. IEEE Transactions on Circuits and Systems I: Regular Papers, Vol. 59, No. 2, pp. 409–425. ISSN: 1549-8328.

Shen Y., Hraimel B., Zhang X., Cowan G. E., Wu K. & Liu T. 2010. A novel analog broadband RF predistortion circuit to linearize electro-absorption modulators in multiband OFDM radio-over-fiber systems. IEEE Transactions on Microwave Theory and Techniques, Vol. 58, No. 11, pp. 3327–3335. ISSN: 0018-9480.

Sjöland H., Bryant C., Bassoo V. & Faulkner M. 2010. Switched mode transmitter architectures. In: Steyaert M., van Roermund A. H. & Casier H. (Ed.) Analog circuit design: smart data converters, filters on chip, multimode transmitters. Springer, pp. 325–342. ISBN: 978-90-481-3082-5

Stapleton S. P. & Costescu F. C. 1992. An adaptive predistorter for a power amplifier based on adjacent channel emissions. IEEE Transactions on Vehicular Technology, Vol. 41, No. 1, pp. 49–56. ISSN: 0018-9545.

Tan L. & Jiang J. 2001. Adaptive Volterra filters for active control of nonlinear noise processes. IEEE Transactions on Signal Processing, Vol. 49, No. 8, pp. 1667–1676. ISSN: 1053-587X.

Tehrani A. S., Cao H., Afsardoost S., Eriksson T., Isaksson M. & Fager C. 2010. A comparative analysis of the complexity/accuracy tradeoff in power amplifier behavioral models. IEEE Transactions on Microwave Theory and Techniques, Vol. 58, No. 6, pp. 1510–1520. ISSN: 0018-9480.

Thompson S. C., Ahmed A. U., Proakis J. G., Zeidler J. R., & Geile M. J. 2008. Constant envelope OFDM. IEEE Transactions on Communications, Vol. 56, No. 8, pp. 1300–1312. ISSN: 0090-6778.

Vuolevi J. H., Rahkonen T. & Manninen J. P. 2001. Measurement technique for characterizing memory effects in RF power amplifiers. IEEE Transactions on Microwave Theory and Techniques, Vol. 49, No. 8, pp. 1383–1389. ISSN: 0018-9480.

Wang F., Yang A: H., Kimball D. F., Larson L. E. & Asbeck P. M. 2005. Design of wide-bandwidth envelope-tracking power amplifiers for OFDM applications. IEEE Transactions on Microwave Theory and Techniques, Vol. 53, No. 4, pp. 1244–1254. ISSN: 0018-9480.

White G. P., Burr A. G. & Javornik T. 2003. Modelling of nonlinear distortion in broadband fixed wireless access systems. Electronics Letters, Vol. 39, No. 8, pp. 686–687. ISSN: 1350-911X.

Widrow B. & Hoff M. E. 1960. Adaptive switching circuits. IRE WESCON Convention Record, part 4, pp. 96–104.

Widrow B. & Walach E. 1996. Adaptive inverse control. Upper Saddle River, NJ: Prentice Hall. ISBN: 0-13-005968-4.

Yao J. 2009. Microwave photonics. Journal of Lightwave Technology, Vol. 27, No. 3, pp. 314–335. ISSN: 0733-8724.

Younes M. & Ghannouchi F. M. 2012. An accurate predistorter based on a feedforward Hammerstein structure. IEEE Transactions on Broadcasting, Vol. 58, No. 3, pp. 454–461. ISSN: 0018-9316.

Yu C. & Zhu A. 2012. A single envelope modulator-based envelope-tracking structure for multiple-input and multiple-output wireless transmitters, IEEE Transactions on Microwave Theory and Techniques, Vol. 60, No. 10, pp. 3317–3327. ISSN: 0018-9480.

Zhou D. & DeBrunner V. E. 2007. Novel adaptive nonlinear predistorters based on the direct learning algorithm, IEEE Transactions on Signal Processing, Vol. 55, No. 1, pp. 120–133. ISSN: 1053-587X.

Zhu A., Draxler P. J., Yan J. J., Brazil T. J., Kimball D. F. & Asbeck P. M. 2008a. Open-loop digital predistorter for RF power amplifiers using dynamic deviation reduction-based Volterra series. IEEE Transactions on Microwave Theory and Techniques, Vol. 56, No. 7, pp. 1524–2008. ISSN: 0018-9480.

Zhu A., Draxler P. J., Hsia C., Brazil T. J., Kimball D. F. & Asbeck P. M. 2008b. Digital predistortion for envelope-tracking power amplifiers using decomposed piecewise Volterra series. IEEE Transactions on Microwave Theory and Techniques, Vol. 56, No. 10, pp. 2237–2247. ISSN: 0018-9480.

PAPER I

Performance of adaptive algorithms for compensation of radio over fiber links

In: Proceedings of Wireless Telecommunications Symposium, Prague, Czech Republic, April 2009, pp. 1–5.

Performance of Adaptive Algorithms for Compensation of Radio over Fiber Links

Atso Hekkala and Mika Lasanen
VTT Technical Research Centre of Finland, P.O. Box 1100, FI-90571 Oulu, Finland
firstname.lastname@vtt.fi

***Abstract*—This paper considers the adaptive predistortion of the nonlinear distortions in a Radio over Fiber (RoF) link. In particular, we modify and compare two adaptive algorithms developed originally for the compensation of the linear systems, namely LMS and variable step size normalized LMS (VS NLMS). A recursive least squares (RLS) solution is used as a reference. Our simulation results indicate that over 40 dB improvement of adjacent channel power ratios can be achieved via the predistortion. Furthermore, we show that in the compensation of the nonlinear RoF link, the LMS can be used in such a way that its performance is comparable to more complex RLS.**

Keywords-LMS; polynomial predistorter; predistortion; RLS; RoF; VS NLMS

I. INTRODUCTION

The trend in wireless communication shows an ever increasing need of higher data rates. This requires exploiting spectrally efficient linear modulation techniques, e.g. orthogonal frequency division multiplexing (OFDM), which are very sensitive to nonlinear distortions. In a cellular architecture, small cells are needed due to high capacity requirements. A large number of conventional basestations becomes expensive and, on the other hand, interference between neighboring users and frequent handovers limit the increase of the system capacity.

A Radio over Fiber (RoF) concept has been introduced to manage these problems, see e.g. [1]. In the RoF concept, conventional basestations can be replaced by simple Remote Antenna Units (RAUs) connected through optical fibers to a Central Unit (CU). Instead of having a signal processing in the RAUs, almost all the processing can be centralized to the CU allowing the RAUs to be as simple and inexpensive as possible [2]. The RoF concept enables distributed antenna usage i.e. a centralized processing with perfect cooperation between the RAUs. Handovers and inter-cell interference mitigation are handled easier by the CU via RoF network.

Due to its low attenuation and enormous bandwidth, optical fiber technology is the advantageous choice to build the needed transparent interconnections between the RAUs and CUs. One major problem that may be encountered in these RoF links are nonlinear distortions experienced in the various cost-efficient devices [3].

Due to its simplicity and easy implementation in general, a predistortion has been found an attractive solution for the compensation of the RoF nonlinearities. In [4], the asymmetric compensation of the RoF links is proposed. They use a higher order Volterra series filter based compensation scheme and recursive least squares (RLS) for the adaptation. However, these solutions may be too complex for practical systems. In [5], a look-up table based predistorter is proposed to compensate RoF link nonlinearities.

To compensate linear systems, a variable step size normalized LMS (VS NLMS) algorithm is proposed in [6]. They also compare the performance of the several LMS based algorithms. The adaptive identification of the nonlinear Wiener system using the LMS algorithm is studied in [7]. In [8], the RLS solution is proposed to use in the compensation of the nonlinear power amplifier.

In this paper, we study and compare different adaptive algorithms for predistortion of a RoF link, namely the LMS and VS NLMS. As an effective but too complex algorithm for practical systems, the RLS solution is used as a reference to the LMS methods. In particular, we modify the LMS methods, which have been originally developed for the compensation of the linear systems, to handle also the higher order nonlinear terms of the signal. To the best of the authors' knowledge, that kind of modifications of the LMS algorithms have not been discussed in detail in the compensation papers. We also discuss the complexity of the algorithms. In this work, we use a polynomial based predistorter due to its flexibility and generality. In addition, it can consider memory effects in an easier manner than the look-up table based predistorter.

The rest of the paper is organized as follows. In Section II, we introduce the system model. Then, we discuss the adaptive algorithms in Section III. In Section IV, we show some simulation results. Finally, Section V includes the conclusion of the paper.

II. SYSTEM DESCRIPTION

In this section, we describe the system model via a block diagram. In addition, we present the model for the RoF link and discuss its compensation.

A. *Simplified system model*

The simplified block diagram of the system model is depicted in Fig. 1. An input signal is fed to a digital predistorter, which compensates nonlinearities introduced in a RoF link. An adaptive controller determines the parameters of the digital predistorter by comparing a feedback signal from a remote antenna unit with a reference signal, i.e. the original input signal.

A complex baseband modeling is utilized using sampling frequency of 76.8 MHz. An orthogonal frequency division multiplexing (OFDM) signal having 1024 subcarries is used as the input signal. The signal model follows closely the 3rd

This work has been performed in the framework of the FUTON FP7 ICT-2007-215533 project, which is partially funded by the European Community.

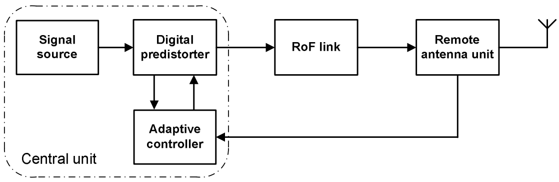


Figure 1. Block diagram of the simplified system model.

Generation Partnership Project (3GPP) specifications [9]. Circulated clipping and filtering to reduce peak-to-average power ratio to 8 dB is applied to the generated signal. Adjacent channel power ratios (ACPRs) are used as performance measures.

B. Radio over fiber model

A laser diode is the main source of the nonlinear distortions in the RoF link. In addition, an optical fiber and photo diode can produce the nonlinearity. Strictly speaking, considering the nonlinearity, the RoF link includes also memory effects. However, well below the resonance frequency of the laser diode, the nonlinearity of the RoF link can be assumed as a memoryless or actually quasi-memoryless that can be described by amplitude-to-amplitude (AM/AM) and amplitude-to-phase (AM/PM) characteristics [4].

In this work, we use the model of the RoF link nonlinearities developed in [10]. The model is based on the experimental AM/AM and AM/PM measurements of the typical RoF link. Using third order polynomials, the output power P_{out} and phase shift ϕ_{shift} of the RoF link can be given by [10]

$$\begin{aligned} P_{out} &= 1.3762p - 0.83406p^2 + 0.16306p^3 \\ \phi_{shift} &= 2.548 - 1.696p + 0.796p^2 + 0.124p^3 \end{aligned} \qquad (1)$$

where p is the input signal power. To illustrate the nonlinear behavior of the model, the AM/AM and AM/PM characteristics are shown in Fig. 2.

C. Digital predistortion

For adaptive compensation of the quasi-memoryless RoF link, we use a polynomial predistorter structure. The polynomial predistorter output z can be given by

$$z(n) = \sum_{k=1}^{K} a_k x(n)|x(n)|^{k-1}, n = 1,2,...,N \qquad (2)$$

where x is the input signal of the predistorter, K is the maximum predistorter order, N is the length of the signal, and a_k is the polynomial coefficient.

In this work, the adaptive identification of the nonlinear predistorter is done using an indirect learning architecture, which is the form of the nonlinear adaptive inverse control as discussed in [11]. See the block diagram of the indirect learning architecture in Fig. 3 [12]. In the indirect learning architecture, the predistorter-training block, i.e. the postdistorter, is driven by the RoF link output y (normalized by a RoF link gain G) and the predistorter output z. In order to achieve the inverse of the RoF link, the postdistorter block

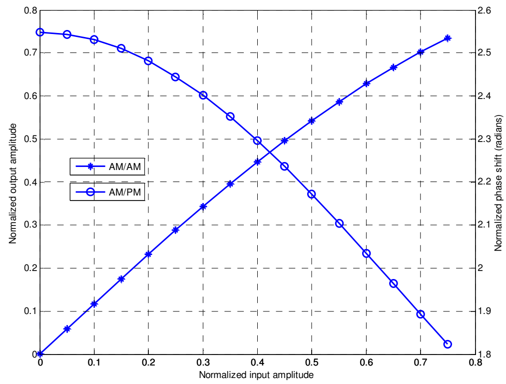


Figure 2. AM/AM and AM/PM characteristics of the RoF model.

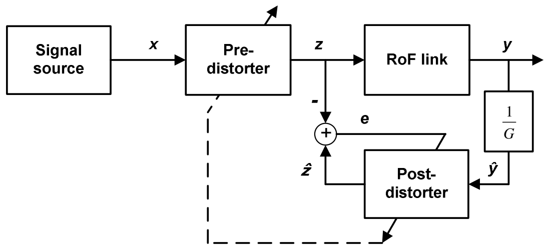


Figure 3. Compensation using indirect learning architecture. Dashed line indicates the copying of the postdistorter to the predistorter after adapting the whole signal block.

adjusts its parameters using an adaptive optimization algorithm. After processing the whole adaptation signal block, say 4000 samples, the inverse model, i.e. the postdistorter, is directly used as the nonlinear predistorter. The adaptation is not performed in real time but offline using stored signals. To obtain the predistorter coefficients a_k in (2), we study different adaptive algorithms described in the next section.

III. Adaptive Algoritms

In this section, we present two well known recursive adaptive, i.e. the LMS and VS NLMS, algorithms. We introduce modifications that make them applicable to nonlinear systems. We use the recursive least square (RLS) solution, proposed in [8], as a reference for the LMS methods.

A. LMS

The conventional LMS algorithm can be given by the following form [13]

$$\begin{aligned} w(n+1) &= w(n) + \mu_{\mathrm{LMS}} e^*(n)\hat{y}(n) \\ e(n) &= z(n) - w(n)\hat{y}(n) \end{aligned} \qquad (3)$$

where $(\cdot)^*$ denotes complex conjugate, $w(n)$ is the filter weight vector, $\hat{y}(n)$ is the feedback signal vector for the adaptation, μ_{LMS} denotes the step size, and $z(n)$ represents the desired signal. The LMS algorithm is widely used due to its low complexity. The main limitation of the algorithm is the trade-off between its convergence speed and steady-state misadjustment. That is because both of them are governed by the same parameter.

The step size dependency of the signal power is discussed in [14 p. 645]. The upper limit of the step size is inversely proportional to the signal power. Thus, we assume that halving the signal power, doubling the step size is required to have an unchanged performance. In addition, in [7], when identifying a nonlinear Wiener system, the step size of the LMS algorithm is scaled according to the signal power. We assume that the speed of the convergence increases by using the individually scaled adaptation step sizes for the different nonlinear orders of the signal.

In this paper, we extend the conventional LMS approach applying scaled step sizes to the LMS adaptation of the nonlinear polynomial predistorter. Therefore, to control also higher order nonlinear terms in $\hat{y}(n)$, we introduce

$$\mathbf{u}(n) = \begin{bmatrix} u_1(n) & u_2(n) & \ldots & u_k(n) & \ldots & u_K(n) \end{bmatrix}^{\mathrm{T}} \tag{4}$$

where $u_k(n) = \hat{y}(n)|\hat{y}(n)|^{k-1}$ and $[\cdot]^{\mathrm{T}}$ denotes matrix transpose. In addition, to keep the step sizes within reasonable levels relative to $\mathbf{u}(n)$, we normalize them as follows

$$\begin{aligned} &\boldsymbol{\mu}_{LMS} = \mu_{LMS}\,\mathrm{diag}\left[(\sigma_1^2)^{-1} \;\ldots\; (\sigma_k^2)^{-1} \;\ldots\; (\sigma_K^2)^{-1}\right] \\ &\text{where } \sigma_k^2 = \tfrac{1}{N}\textstyle\sum_{n=1}^{N} |u_k(n)|^2. \end{aligned} \tag{5}$$

Note that these normalizations do not need to be done in actual adaptation if signal powers are known beforehand. Thus, the modified LMS algorithm can be given by

$$\begin{aligned} \mathbf{w}(n+1) &= \mathbf{w}(n) + \boldsymbol{\mu}_{\mathrm{LMS}}\, e^*(n)\mathbf{u}(n) \\ e(n) &= z(n) - \mathbf{w}^{\mathrm{H}}(n)\mathbf{u}(n) \end{aligned} \tag{6}$$

where $[\cdot]^{\mathrm{H}}$ denotes Hermitean transpose.

B. VS NLMS

Several variable step size (VS) LMS algorithms have been proposed to obtain both a fast convergence and a small steady-state error, see e.g. [6] and references therein. The algorithm of the VS NLMS is given by [6]

$$\begin{aligned} w(n+1) &= w(n) + \mu(n)e^*(n)\hat{y}(n) \big/ \|\hat{y}(n)\|^2 \\ \mu(n) &= \mu_{\max} \|p(n)\|^2 \big/ (\|p(n)\|^2 + C) \\ p(n) &= \alpha p(n-1) + (1-\alpha)\hat{y}(n)e^*(n) \big/ \|\hat{y}(n)\|^2 \end{aligned} \tag{7}$$

where α is the smoothing factor ($0 \leq \alpha < 1$), C is the positive constant, $\mu_{\max}$ represents the maximum step size, and ||·|| is the Euclidean norm of the vector. The error vector $e(n)$ is as in (3).

To apply the VS NLMS algorithm to the compensation of the nonlinearities, we modify (7) similarly as the LMS algorithm. We define $\mathbf{u}(n)$ same as above. In addition, we normalize the maximum step size $\mu_{\max}$ and the constant C as follows

$$\begin{aligned} \boldsymbol{\mu}_{max} &= \mu_{\max}\,\mathrm{diag}\left[(\sigma_1^2)^{-1} \;\ldots\; (\sigma_k^2)^{-1} \;\ldots\; (\sigma_K^2)^{-1}\right] \\ \mathbf{C} &= C\,\mathrm{diag}\left[\sigma_1^2 \;\ldots\; \sigma_k^2 \;\ldots\; \sigma_K^2\right] \end{aligned} \tag{8}$$

In addition to these, we slightly modify (7) to get the following VS NLMS algorithm for the nonlinear polynomial predistorter

$$\begin{aligned} \mathbf{w}(n+1) &= \mathbf{w}(n) + \boldsymbol{\mu}(n)e^*(n)\mathbf{u}(n) \\ \boldsymbol{\mu}(n) &= \boldsymbol{\mu}_{\max} |\mathbf{p}(n)|^2 \big/ (|\mathbf{p}(n)|^2 + \mathbf{C}) \quad . \\ \mathbf{p}(n) &= \alpha\mathbf{p}(n-1) + (1-\alpha)\mathbf{u}(n)e^*(n) \end{aligned} \tag{9}$$

In our case, the length of the adaptive filter is one. Therefore, it is not possible to do normalization to **w** and **p**. These parameter values would go to infinity with division by zero. In addition, the scaling of **μ** corresponds effectively to the scaling of w in (7); now we have a long averaging period.

C. RLS

We use the RLS solution, defined in [8], as a reference for the performance tests. The RLS solution can be given by

$$\begin{aligned} \mathbf{w}(n+1) &= \mathbf{w}(n) + \boldsymbol{\mu}_{\mathrm{RLS}}(n)\mathbf{u}(n)e^*(n) \\ \boldsymbol{\mu}_{\mathrm{RLS}}(n) &= \lambda^{-1}\boldsymbol{\mu}_{\mathrm{RLS}}(n-1) - \tfrac{\lambda^{-2}\boldsymbol{\mu}_{\mathrm{RLS}}(n-1)\mathbf{u}^*(n)\mathbf{u}^{\mathrm{T}}(n)\boldsymbol{\mu}_{\mathrm{RLS}}(n-1)}{1+\lambda^{-1}\mathbf{u}^{\mathrm{T}}(n)\boldsymbol{\mu}_{\mathrm{RLS}}(n-1)\mathbf{u}^*(n)} \end{aligned} \tag{10}$$

where λ is the forgetting factor and $\mathbf{u}(n)$ is defined same as above. To have faster convergence, we use a small RLS forgetting factor for the first adaptation signal block [11]. Then, we continue with a large value to introduce more averaging.

IV. Results

In this section, we demonstrate the performances of the adaptive algorithms and compare them to each other. We also highlight some points we see essential in algorithm complexity point of view.

In the simulations, the RoF link is modeled using (1). The RAU and the feedback link are assumed ideal. Please, see the discussion in the Section V about the problem of the feedback in RoF concept.

The OFDM signal having 1024 subcarries and 10 MHz bandwidth is used in the simulations. The maximum amplitude of the signal is normalized to 0.75, see Fig. 2. To train the postdistorter in each iteration, the signal block with 4000 samples is used. For all the methods, the same input signal is used. However, the adaptation signal block is different in each iteration. We noticed, that a larger number than 5 as the predistorter order K does not give any improvement in terms of output signal adjacent channel power ratio (ACPR). In addition, it is enough to use only odd order terms for the predistorter. These affect directly also to (4), (5), and (8), so that k gets only values 1, 3, and 5. When plotting ACPRs in decibels relative to the carrier power, we calculate the average value of the lower and higher adjacent channel powers, i.e. the channels centered at -10 and +10 MHz.

Simulation parameters for the LMS algorithms are as follows. The step size for the conventional LMS algorithm is set to 1, see (3). For the modified LMS (from now on the LMS) methods, we have μ_{LMS} = 0.02 in (6), μ_{max} = 0.02, C = 0.0000002, and α = 0.9 in (9). These parameters have been found during several tests in our system model and they give the maximum achievable speed of the convergence. However, it should be noted that due to the need of tuning many parameters, it is possible that we did not find the optimal set of the parameters for the VS NLMS. Note also, that the scope of this paper is not to study how to find the appropriate parameter values.

To illustrate an achievable improvement of the ACPR performance in our system model, we show signal spectra at the output of the compensated and uncompensated RoF links in Fig. 4. The compensated spectrum is achieved after two iterations of the RLS algorithm.

Fig. 5 shows the achievable ACPRs at the output of the RoF link after subsequent iterations using the LMS and conventional LMS algorithms. As can be seen, the use of the scaled step sizes for the different predistorter orders increases the convergence speed dramatically.

In Fig. 6, we show the achievable ACPRs of the output signal after subsequent iterations using different recursive algorithms. Using the RLS solution, we achieve almost -70 dB ACPR already after two iterations. To achieve similar ACPR with the LMS methods, 7-8 iterations are needed. The use of the VS NLMS gives only a bit faster convergence than the LMS. The main reason for that is that we cannot increase the maximum step size μ_{max} much enough due to stability problems. Using the LMS methods, the variances of the ACPRs are also roughly at the same level.

As can be seen from Fig. 6, the variation of the ACPRs is larger using the LMS than the RLS solution. The reason for that is clearly due to trade-off between its convergence speed and steady-state misadjustment in the LMS. It is possible to decrease the variation by decreasing the step size after the algorithm is converged, i.e. we turn on a tracking mode. In the tracking mode, the step size is reduced to one tenth of the original step size. We turn on the tracking mode 1, 2, and 3 when an average error between input and output signals goes below -50 dB, -60 dB, and -70 dB, respectively. The average error is calculated over 4000 samples after each iteration. In practice, a more efficient solution could use the error signal or its energy with averaging as a reference for switching to the tracking mode.

Fig. 7 shows the ACPR performance of the LMS method using different tracking modes. Carefully selecting the tracking mode, the convergence speed of the algorithm does not become slower; see the curve of the tracking mode 3 in Fig. 7. On the other hand, the tracking mode 1 demonstrates that a very slow convergence takes place with the non-optimized parameter usage. However, as can be seen, the steady-state misadjustment is significantly reduced.

Based on the simulations in our system model, it seems that it is preferable to use the LMS instead of the VS NLMS because they give comparable performances, while the LMS has the lower complexity as discussed in [15].

Some rough estimates on the complexity of the algorithms can be also seen from the equations. Considering the LMS, the

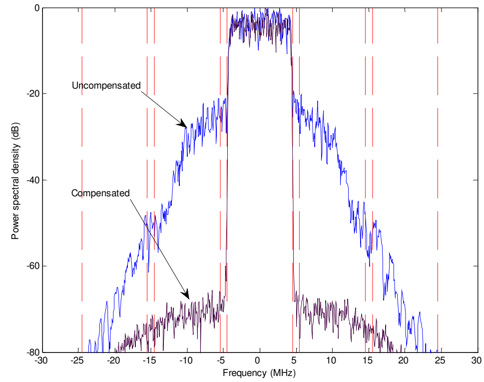


Figure 4. Signal spectra at the output of the uncompensated and compensated RoF link.

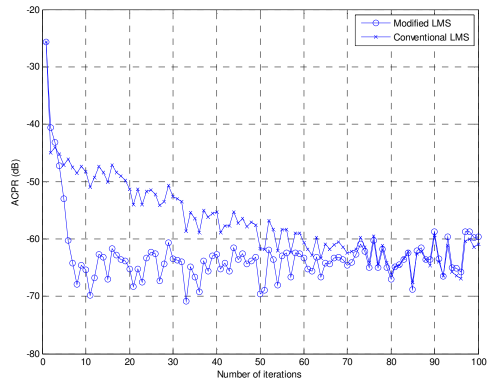


Figure 5. Achievable ACPRs of the output signal after subsequent iterations using the conventional and modified LMS.

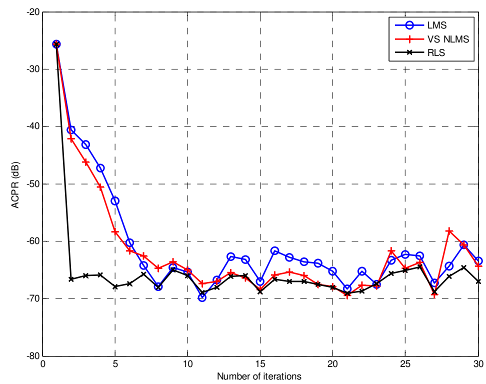


Figure 6. Achievable ACPRs of the output signal after subsequent iterations using the LMS, VS NLMS, and RLS.

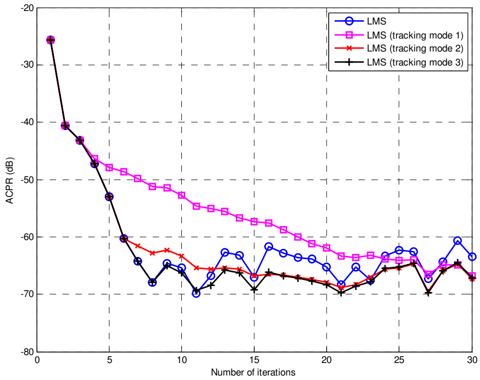


Figure 7. Achievable ACPRs of the output signal after subsequent iterations using the LMS with different tracking modes.

normalizations can be done in an offline process. Thus, there are only a few multiplications and no division in (6). In the VS NLMS, more multiplications are needed, see (9). Furthermore, a division is required and this is more complex than a multiplication. Even though, the VS NLMS is a bit more complex than the LMS, it is much less complex than the RLS. In the RLS, matrix operations increase considerably the number of the multiplications and divisions. It is stated in [14], that one of the main problems of the RLS solution is its high complexity. In addition to that, numerical instability may be a problem with the higher orders of the adaptive predistorter. Therefore it is tended to be unsuitable solution for practical systems.

V. DISCUSSION AND CONCLUSION

In this work, we studied the compensation of the RoF link. We introduced and compared two adaptive algorithms for predistortion, namely the LMS and VS NLMS algorithms. The RLS solution was used as a reference for performance measures. The algorithms were modified to handle also the higher order nonlinear terms of the signal.

The results suggest that the LMS algorithm can be used in such a way that its performance is comparable to more complex VS NLMS and RLS. In particular, the use of the LMS gives only a bit slower convergence than the VS NLMS and in the tracking mode it achieves as good ACPR performance as the RLS. Due to its low complexity the LMS algorithm can be seen as a very attractive choice for cost-efficient systems.

Providing the feedback signal from the RAU to the CU is one of the challenging tasks in the adaptive compensation of the RoF link. That is because the feedback branch can be as nonlinear as the RoF link to be compensated. Careful design should be done to avoid confusions when compensating the RoF link with the nonideal feedback. One approach could be to use the knowledge of the already compensated RoF link in uplink direction. This problem clearly needs further studies.

ACKNOWLEDGEMENT

The authors would like to thank Ilkka Harjula and Adrian Kotelba, VTT, Finland, for valuable discussions during the work.

REFERENCES

[1] H. Al-Raweshidy and S. Komaki, Eds., *Radio over Fiber Technologies for Mobile Communications Networks*. Norwood MA: Artech House, 2002.

[2] Fibre optic networks for distributed, extendible heterogeneous radio architectures and service provisioning. FUTON project. [Online]. Available: http://www.ict-futon.eu/

[3] A. R. Shah and B. Jalali, “Adaptive equalisation for broadband predistortion linearisation of optical transmitters,” in *Proc. Inst. Electr. Eng.-Optoelectron.*, vol. 152, pp. 16-32, Feb. 2005.

[4] X. N. Fernando and A. B. Sesay, “Adaptive asymmetric linearization of radio over fiber links for wireless access,” *IEEE Trans. Vehic. Tech.*, vol. 51, pp. 1576-1586, Nov. 2002.

[5] H. Moon and R. Sedaghat, “FPGA-based adaptive digital predistortion for radio-over-fiber links,” Microprocessors and Microsystems, vol. 30, pp. 145-154, 2006.

[6] H.-C. Shin, A. H. Sayed, and W.-J. Song, “Variable step-size NLMS and affine projection algorithms,” *IEEE Signal Process. Lett.*, vol. 11, pp. 132-135, Feb. 2004.

[7] P. Celka, N. J. Bershad, and J.-M. Vesin, “Stochastic gradient identification of polynomial wiener systems: analysis and application,” *IEEE Trans. Signal Process.*, vol. 49, pp. 301-309, Feb. 2001.

[8] R. Marsalek, “Contribution to the power amplifier linearization using digital baseband adaptive predistortion,” Ph.D. dissertation, Inst. Gaspard Monge, Univ. de Marne la Vallee, France, 2003.

[9] Physical layer aspects for evolved Universal Terrestrial Radio Access (UTRA) (Release 7), 3GPP Technical Report 25.814 version 7.1.0, 2006.

[10] X. N. Fernando and A. B. Sesay, “Higher order filter based predistortion for nonlinear distortion compensation of radio over fiber links,”in *Proc. IEEE Int. Conf. Commun.*, pp. 367-371, New Orleans, LA, Jun. 2000.

[11] M. Lasanen, A. Kotelba, A. Hekkala, P. Järvensivu, and A. Mämmelä, “Adaptive predistortion architecture for nonideal radio transmitter,” in *Proc. IEEE Vehic. Tech. Conf. spring*, pp. 1256-1260, Singapore, May 11-14, 2008.

[12] L. Ding et al, “A robust digital baseband predistorter constructed using memory polynomials,” *IEEE Trans. Commun.*, vol. 52, pp. 159-165, Jan. 2004.

[13] B. Widrow and E. Walach, *Adaptive Inverse Control*. Upper Saddle River, NJ: Prentice Hall, 1996.

[14] J. G. Proakis, *Digital Communications*. 3rd ed., New York: McGraw-Hill, 1995.

[15] T. Yang and B. Shahrrava, “Performance of variable step-size LMS algorithms for linear adaptive inverse control systems,” in *Proc. IEEE Canadian Conf. Elect. and Comp. Eng.*, Saskatchewan, Canada, pp. 755-758, May 1-4, 2005.

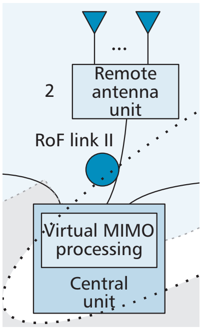
PAPER II

Analysis of and compensation for non-ideal RoF links in DAS

In: IEEE Wireless Communications,
Vol. 17, No. 3, pp. 52–59.

ANALYSIS OF AND COMPENSATION FOR NON-IDEAL ROF LINKS IN DAS

ATSO HEKKALA, MIKA LASANEN, AND ILKKA HARJULA,
VTT TECHNICAL RESEARCH CENTRE OF FINLAND
LUIS C. VIEIRA, NATHAN J. GOMES, AND ANTHONY NKANSAH, UNIVERSITY OF KENT
STEFFEN BITTNER, FABIAN DIEHM, AND VINCENT KOTZSCH,
DRESDEN UNIVERSITY OF TECHNOLOGY



The authors consider radio over fiber links as an essential part of the DAS, connecting the central unit with the remote antenna units. In particular, they analyze and discuss delays and nonlinearities stemming from the RoF links.

ABSTRACT

Distributed antenna systems have been found to be an elegant solution for the problems arising in high-data-rate wireless communication, particularly in large service areas. This article considers radio over fiber links as an essential part of the DAS, connecting the central unit with the remote antenna units. In particular, we analyze and discuss delays and nonlinearities stemming from the RoF links. In addition, we study the compensation for these impairments. Our studies indicate that the RoF links are a viable and cost-effective solution for implementing the DAS, although some of the RoF link non-idealities require compensation.

INTRODUCTION

The provision of broadband services to everyone is considered to be one of the key enablers of the so-called information society. Traditionally, optical fibers have been used for delivering very-high-data-rate services to the end user. Following the very high acceptance of mobile devices across the globe, it is obvious that end users would like to see wireless services similar to those offered by wired connections.

Due to the need for high data rates (~1 Gb/s), spectrally efficient modulation techniques such as orthogonal frequency-division multiplexing (OFDM) have to be used. These techniques are very sensitive to nonlinear distortions. In addition, in a cellular architecture small cells are needed. This increases the number of conventional and expensive base stations needed to cover the service area. Furthermore, small cells increase the interference between neighboring users and the number of handovers, limiting the system capacity. Finally, the provision of high data throughput in wireless systems requires the use of multiple antennas exploiting the scattering properties of the wireless medium. The physical size of the transceivers, especially in the mobile terminal (MT), restricts the number and spacing of the antenna elements in a multiple-input multiple-output (MIMO) link.

As a solution to the aforementioned problems, the concept of virtual MIMO has been proposed [1]. In such a system the MT can be connected simultaneously to several remote antennas of base stations that are placed in physically separate locations and host one or more antenna elements. The signals from different antennas are processed jointly by a central processing unit (CU); thus, the effective multiplexing gain of the virtual MIMO system can be raised sufficiently to meet the high capacity requirement. At the same time, the handovers and intercell interference mitigation are handled more easily with joint processing. In addition, energy and cost savings are achieved due to the use of low-power and cost-effective remote antenna units (RAUs). The end users also benefit from the use of distributed antennas, as the transmit power budget is considerably improved, resulting in reduced power consumption of the devices and therefore longer operational times. The distributed antenna system (DAS) forms a virtual MIMO where the RAUs are connected to the CU via high-data-rate radio over fiber (RoF) links. RoF links may outperform possible digital or wireless links due to benefits in transparency, high available bandwidth, reliability, interference tolerance, low attenuation, relatively low cost, and simple design [2, 3].

While in conventional wireless communication systems the major sources of impairments are due to imperfections of the components of the radio frequency (RF) branch, particularly power amplifiers (PAs) and mixers, the considered system has to cope with additional signal distortions coming from the optical distribution

This work has been performed in the framework of the FUTON FP7 ICT-2007-215533 project, which is partially funded by the European Community. Luis C. Vieira is sponsored by the Brazilian Government through CNPq and UTFPR, whose support is gratefully acknowledged.

1536-1284/10/$25.00 © 2010 IEEE

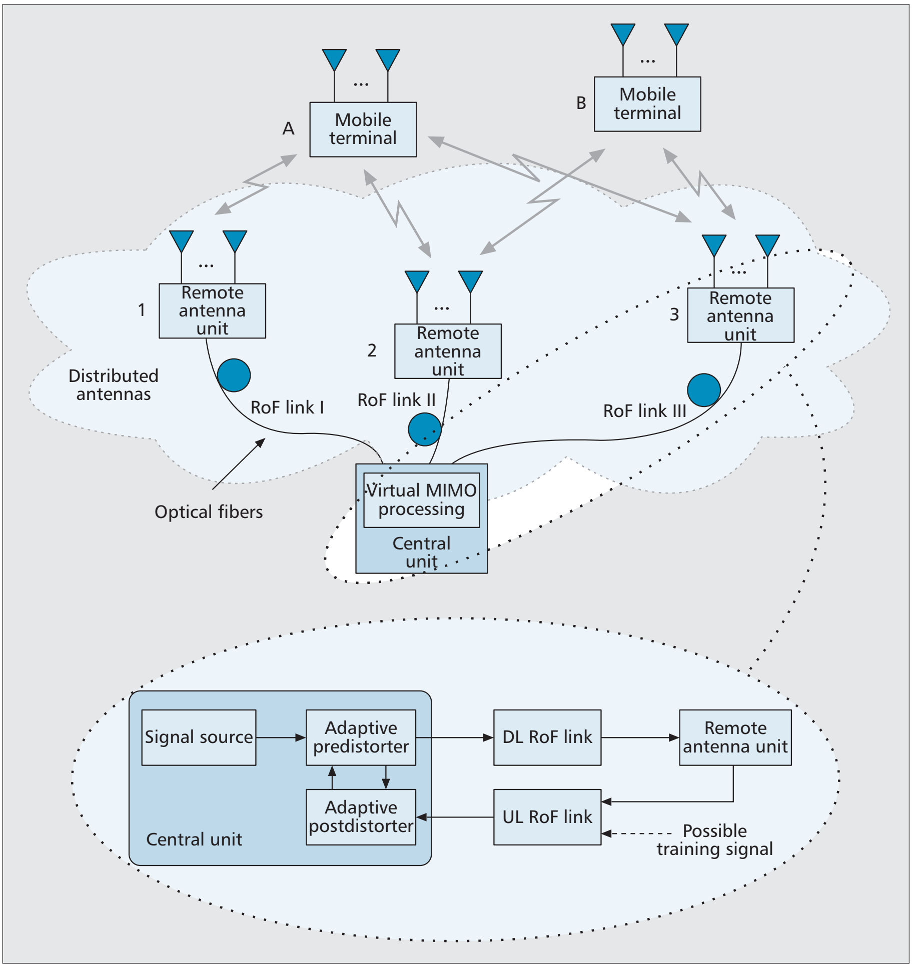


Figure 1. *Simplified DAS and RoF link.*

> The performance of the RoF optical links is heavily dependent on the optical transmitter, since both noise and nonlinear distortion of the optical modulation device often dominate over the photodetection device.

network. The aim of this article is to provide a detailed discussion of the signal impairments stemming from the RoF links. The most severe distortions on the output signal of an RoF link are caused by electro-optical device nonlinearities, but other effects such as long propagation delays also have to be taken into account.

The rest of the article is organized as follows. The system model is presented in the next section. After that, the analysis of the distortions present in the proposed RoF link is given. Then compensation techniques for these distortions are discussed. Finally, conclusions are given at the end of the article.

System Description

A DAS for broadband wireless as proposed in [1] is shown in Fig. 1. It consists of a CU connected via optical fibers (i.e., RoF links) to several RAUs. The CU can serve several MTs through multiple RAUs. All the signal processing tasks are centralized, and performed at the CU, thus enabling the concept of the virtual MIMO. In the EU project FUTON, a radio interface based on those being specified in Third Generation Partnership Project (3GPP) Long Term Evolution-Advanced (LTE-A) and WiMAX 802.16m is defined (Table 1). At least four radio channels are required in each direction between the CU and each RAU to support sectorization and virtual MIMO. As the system is considered for larger service areas, such as city centers, a single-mode fiber distribution system is envisaged. Such a distribution system can be made compatible with fixed access topologies, such as passive optical networks [4].

The connections between the CU and the RAUs are implemented by RoF technology. In this optical technology, analog RF signals are transmitted transparently over the fiber distribution system. The fiber is characterized by low attenuation and high bandwidth. Analog signal transmission leads to simpler RAUs and the analog signals generally occupy less bandwidth than their baseband equivalents. In addition, analog signal transmission, as opposed to baseband transmission, is necessary for the joint pro-

Parameter	Requirement
Number of radio channels per link direction	4
Radio channel bandwidth (up to)	100 MHz
Modulation scheme (up to)	1024-QAM
Number of OFDM subcarriers (up to)	2048
OFDM symbol length	20.48 μs
Cyclic prefix length	2.0 μs
Minimum approach distance	2 m
Mobile terminal transmit power (min.)	–10 dBm
Mobile terminal transmit power (max.)	+33 dBm

Table 1. *Radio system parameters.*

cessing of signals (e.g., in the use of maximum ratio combining). Although the analog signals could be transported in digitized format, as is currently specified for remote radio heads in WiMAX and LTE, for systems such as that specified in Table 1, a cost analysis suggests that this will currently be at least an order of magnitude more expensive [5]. An analysis of the performance of RoF links for this system also shows little degradation compared to the wireless system performance itself, as long as uplink power control over the range specified in Table 1 is implemented [6].

A simplified block diagram of one RoF link showing the compensation of the nonlinearities in downlink (DL) direction and the possible use of the uplink (UL) RoF link as feedback for the compensation is also depicted in Fig. 1. An adaptive predistorter is introduced to compensate for the nonlinearities of the DL RoF link. For the adaptation, a feedback signal is provided from the RAU back to the CU (e.g., through the UL RoF link). In order for the UL RoF link to be used for the feedback, its own nonlinearities may need to be compensated for using a known training signal from the RAU and an adaptive postdistorter in the CU.

The performance of the RoF optical links is heavily dependent on the optical transmitter, since both noise and nonlinear distortion of the optical modulation device often dominate the photodetection device [2]. The distortions on the output signal caused by electro-optical device nonlinearities depend on the input signal amplitude and the modulation bandwidth.

The most common modulation techniques for RoF links are direct modulation and external modulation. In the former, a single device serves as both the optical source and the RF/optical modulator. Generally, distributed feedback (DFB) lasers are used due to their better spectral and noise characteristics compared to Fabry-Perot lasers [2]. The external modulation method requires an additional optical component as modulator — usually a Mach-Zehnder modulator (MZM), this solution being more expensive than the direct modulation link. DFB lasers can suffer from chirp, relative intensity noise, and nonlinear distortion, whereas MZMs have greater insertion loss than directly modulated lasers (at comparable optical power levels), and also exhibit nonlinear distortion and bias drifting.

Single-mode optical fibers are the common choice for long-haul applications, due to their low attenuation. Chromatic dispersion is the major concern with this type of fiber. However, this dispersion is insignificant up to around 2 GHz and to several hundreds of kilometers of fiber length [3]. Generally, other fiber distortions can be neglected for relatively low-power RoF links. Photodiodes may saturate at high optical power, causing some nonlinear effects. This nonlinearity can be avoided by an adequate link design, ensuring that not too high optical power is detected by the photodiode.

Aiming at data rates above 1 Gb/s, one easily approaches the physical limits set by the analog RF front-end through aperture clock jitter, I/Q imbalances, nonlinearities of the PA, and phase noise (PN) [7]. Cost-effective design of advanced wireless systems requires awareness and minimization of the harmful effects on performance of the RF impairments mentioned above. In this regard, when the carrier frequency is on the order of a few gigahertz and the fiber length is only a few kilometers, nonlinear distortions of the analog signal constitute the major impairment coming from the optical part of the system, not forgetting a non-ideal RF front-end. The effects of the non-ideal RF front-end are briefly discussed next.

DC offsets mainly occur due to self-mixing of the signals caused by non-perfect isolation between the oscillator and the PA, and lead to a higher probability of clipping events in the analog-to-digital conversion process. Commonly, these offsets are effectively precompensated for by dedicated circuits already in the analog domain. I/Q imbalance denotes the imperfect orthogonality between the in-phase and quadrature components during the complex mixing process. In today's commercially available components, the image signal is multiple orders of magnitude weaker than the information carrying signal. Phase noise stems from imperfections of oscillators in the transmitter and receiver RF front-ends and results in a phase distortion of the signal. Generally, PN can be one of the major sources of inter carrier interference in OFDM systems and constitutes a major performance limitation, especially in the high signal-to-noise ratio (SNR) regime for high-order modulation format like 1024-quadrature amplitude modulation (QAM). The use of high order modulations is important for the envisioned peak transmission rates of 1 Gb/s especially for one user in a line-of-sight (LOS) transmission environment. That is because the link capacity for one user in the LOS case does not increase linearly with the number of antennas as it does in theory for the non-LOS environment where rich scattering helps the receiver to resolve the spatially multiplexed signals. Practical PAs exhibit nonlinear transfer characteristics and induce distortions into the signal as well as out-of-band radiation. Next to the poor bit error rate (BER), the increase in out-of-band emissions can be several tens of decibels at certain frequencies. Both effects require the use of an adequate predistortion technique [8]. Compensation for the RoF link and power amplifier connected in series is studied by the authors in [9]. In addition, reducing a high peak-to-average power ratio of the OFDM signal is one well-known approach to mitigate the effects of the nonlinear analog parts. However, these topics are out of the scope of this article.

MEASUREMENTS AND MODELS OF ROF LINK

Memoryless nonlinearity in directly modulated RoF links comes mainly from the static light power-current transfer characteristic of the laser. From this characteristic, the current applied to the laser diode is limited by saturation at the high end and by threshold current at the low end, leading to a maximum input RF power the laser can handle before distortion becomes significant. Besides, under dynamic operation, the transfer function might have strong variations with frequency.

From a physical approach, the dynamic nonlinearities of the laser are commonly modeled by a pair of nonlinear differential equations known as single-mode rate equations, which provide a description of the physical phenomena that govern the interaction between photons and electrons in the active region of the laser.

An RoF link model has been presented in [9] using AM/AM and AM/PM measurement techniques. Such an empirically based modeling approach provides the nonlinear amplitude and phase characteristics of a system (or device) obtained from measurements of the RF input-output signals. The model was extracted from an experimental directly modulated DFB-based RoF link. A more detailed description of the experimental setup can be found in [9].

The AM/AM amplitude and AM/PM phase distortions are modeled by two rational functions [9]; their characteristics are shown in Fig. 2. Measurements of the RoF link are shown as well. Rational functions are used due to their good interpolation and extrapolation properties, and wide range of handled shapes.

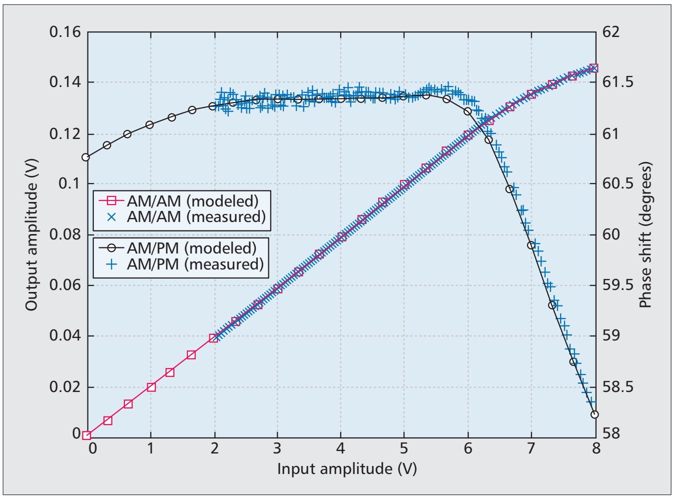


Figure 2. *Measurements and models of RoF link.*

ANALYSIS OF DISTORTION IN ROF LINKS

DELAY EFFECT ANALYSIS AND COMPENSATION

In conventional cellular systems, where each mobile terminal communicates with a single base station, timing synchronization in the downlink guarantees that the transmitted symbols fall into the detection window of the terminals. In the uplink timing advance is commonly applied so that the transmissions from terminals at different locations arrive at the base station in an aligned fashion and at the desired time. Thus, propagation delay differences are compensated for efficiently.

This picture changes for distributed systems, where mobile terminals are served by multiple RAUs. In this case the signals originating from multiple RAUs arrive with different delays at the mobile terminals, depending on the position of the users within the service area. Thus, it is not possible for the users to adjust their detection window for synchronous signal reception. Likewise, in the uplink it is not possible to avoid delay differences through timing advance. Thus, there is a duality between up- and downlink in these systems concerning delay differences, and we do not distinguish between the two directions in the following.

Using OFDM, fully synchronous reception can be relaxed as long as the maximum channel excess delay and propagation delay differences do not exceed the length of the cyclic prefix. However, for a DAS this would potentially require a long cyclic prefix as delay differences can be large. This, in turn, results in a substantial loss of spectral efficiency, as much of the system's power and transmission time is spent on redundancy. If the timing offsets exceed the cyclic prefix, it is well known that the orthogonality of the OFDM subcarriers is lost and additional interference is induced. A model to predict this interference is developed in [10].

For the DAS considered in this article, with joint signal processing at the CU, two sources of delay are introduced in the transmission path. Besides the radio propagation delays that depend on the distances between users and RAUs, additional delays are introduced by the optical fibers that connect the RAUs to the CU. In the literature two different RoF phenomena have been studied. The first concerns a single RoF link, which can consist of several optical fibers. Small delay differences between the fibers typically occur and are mainly caused by variations of the optical cable length due to thermal expansion [11] or on the transmitter side by analog front-end mismatches [12]. These phenomena cause shifts in the signal phases between the signals transmitted or received by different antenna elements. The differences are typically less than 25 ns for 1 km [11], and can be estimated and compensated for at the baseband receiver. A methodology for phase and amplitude correction is presented in [12].

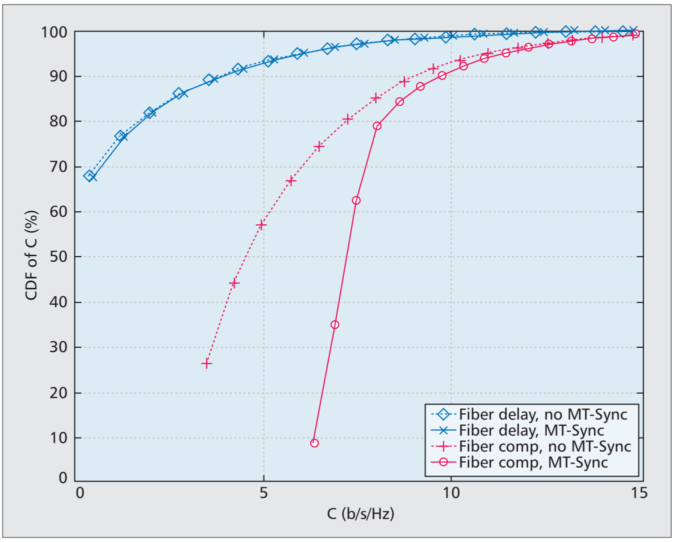


Figure 3. *Impact of delay compensation techniques.*

A more evident optical cable delay challenge originates from the signals travelling between the CU and different RAUs. Because each RAU has a different distance to the CU, RAUs do not transmit at the same time as they should to minimize interference effects. However, an interesting and straightforward solution has been proposed in [13]. The approach measures the delays of all RoF links during a power-up phase. After knowing the delays, each signal going to or coming from an RAU is delayed so that all RAUs transmit at the same time.

In general, the cyclic prefix length should be carefully chosen to maximize system performance. Furthermore, resource allocation and user-to-RAU grouping should be considered to, say, only serve users jointly that experience a similar delay behavior. In the following we compare spectral efficiencies of a typical DAS setup with and without compensation techniques. For the evaluation, we consider a scenario where one MT is served by three RAUs. The CU is located at one of the RAUs. The other RAUs are connected via fiber links. Since in real deployments fibers can hardly be deployed in a straight line, and excess fiber is commonly used to gain flexibility for future changes, we assume that fiber distance is five times the air distance. To calculate the fiber delays, we furthermore assume a refractive index of 1.45, which is commonly found. Thus, the fiber signal speed is about 70 percent of the speed of light. All other simulation parameters are given in Table 2.

For this setup, we calculate the spectral efficiency of the MT for random user drops within the collaboration area and for different delay compensation techniques. The effect of delay differences is modeled as a signal-to-interference-plus-noise ratio (SINR) degradation as described in [10]. To calculate the spectral efficiency, we calculate the capacity and weight it with the bandwidth efficiency factor that accounts for the loss in spectral efficiency due to the cyclic prefix. Figure 3 compares the cumulative distribution functions (CDFs) of the spectral efficiency in the service area for different compensation techniques (values on the ordinate indicate the percentage of service area, where the spectral efficiency is less than or equal to the corresponding values on the abscissa). We consider the fiber delay compensation as proposed in [13] and MT synchronization, where the receiver adjusts its reception window to be synchronous with the best transmission link. Clearly, using both compensation techniques can significantly increase the spectral efficiency in the service area. However, the effect of the fiber delays is very dominant, and MT synchronization does not yield performance enhancements when the fiber delays are not compensated for. As the fiber delays severely degrade system performance, their compensation is essential to achieve the high target data rates envisaged for DASs.

EVM and BER Analysis

As already noticed, the RoF link induces some phase shift to the signal. The average phase shift to the signal constellation can be seen in Fig. 4, where the rotated constellation points of the distorted signal are shown. When the average phase shift is compensated for (using, e.g., a channel estimation), the residual effect on the signal constellation is shown in Fig. 4. The uncompensated RoF link introduces a noise-like effect that cannot be removed. Therefore, the orthogonality of the subcarriers is reduced, and intersubcarrier interference is increased. Measured error vector magnitude (EVM) for the 64-QAM signal is 1.11 percent, which corresponds to –38.9 dB. The EVM is calculated as a ratio of average error power and average constellation power.

Analytical BER results for nonlinear distortion effects in an ideal additive white Gaussian noise (AWGN) channel with 1024-QAM modulation are shown in Fig. 5. The calculations were carried

Parameter	Value
Carrier frequency	3.5 GHz
RAU Tx power	23 dBm
Power delay profile	Exponential
Channel excess delay	1 μs
Pathloss exponent	3.91
Propagation environment factor	20.64 dB
Noise power per subcarrier	–132 dBm
Inter-RAU distance	$\sqrt{3} * 800$
Fiber length	$\sqrt{3} * 4000$
Refractive index	1.45
OFDM parameters	See Table 1

Table 2. *Simulation parameters.*

out based on [14, p. 278]. The results show that the nonlinear distortion effects cause visible performance degradation, and for a BER of 0.001 this is about 1.75 dB. The performance degradation for smaller constellation sizes was also analyzed, but, for example, for 64-QAM there was no visible degradation in performance. The natural explanation for this is that the required SNR for a low BER is small compared to the distortion level, and therefore the smaller constellation sizes are immune to distortion effects.

The average SNR vs. BER performance of the system with nonlinear distortion effects from the RoF link were also studied via simulations for 1024-QAM modulation. The results are plotted in Fig. 5. The channel models used in the simulations are AWGN and three-tap Rayleigh fading following the example channel given in [14, p. 616]. A simple channel estimator was used in the receiver with a simple and generic pilot structure corresponding to WiMAX UL pilots. It can be seen that the degradation in the AWGN channel follows the analytical results taking into account the performance degradation caused by the imperfect channel estimates, and that the effect of the distortion diminishes in the fading channel case.

Assuming an efficient channel code, the performance degradation could also be endured. On the other hand, in reality we may face an RoF link that introduces more distortion. In addition, in MIMO systems several RoF links are used, and in the air all of these distortions cumulate. Furthermore, PAs of several MIMO transmitters add their distortion to the system. Hence, a goal to minimize transmission of undesired interference may also be feasible here.

Spectral Regrowth

Due to the high peak-to-average power ratio (PAPR) of a multicarrier signal such as OFDM, there is a trade-off between linearity and efficiency in the cost-efficient analog components of the RoF link and power amplifiers as well. To achieve good efficiency, some nonlinearity is tolerated. As discussed earlier, this nonlinearity affects in-band distortions, and out-of-band distortion (i.e., spectral regrowth).

The spectral regrowth due to the nonlinear RoF link is clearly visible, as shown in Fig. 6. The spectra of the ideal and compensated signals are shown as well. The signal bandwidth is 12.5 MHz (i.e., the used fast Fourier transform [FFT] size is 256). For more information on the signal model see [9].

Compensation for RoF Nonlinearities

The compensation for RoF link nonlinearities can be done in the electrical or optical domains. For compensation in the optical domain, optical methods and components are used [2]. The optical compensation methods give comparable performance to electrical compensation, but usually they have economic disadvantages. That is because many of the optical linearization techniques involve the use of duplicate lasers or optical modulators.

Compensation in the electrical domain can take the transfer function of the RoF link as

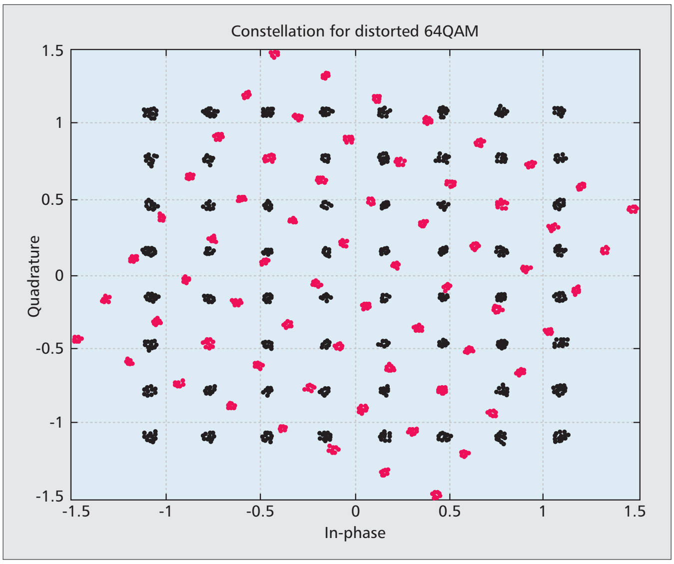


Figure 4. *Signal constellations for 64-QAM. Rotated constellation due to phase shift is shown in red and compensated constellation in black.*

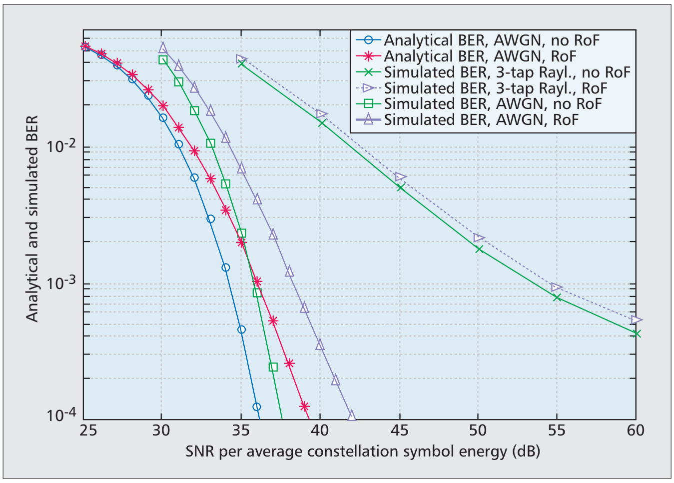


Figure 5. *Theoretical and simulated BER performance with single link with 1024-QAM modulation, AWGN, and 3-tap Rayleigh fading channel model. For theoretical results, distortion of an EVM of 39 dB is assumed.*

given and apply it for the compensation using electronic circuits. Therefore, more general compensation methods can be designed. In addition, economic benefits are obtained due to the use of electrical components from the large semiconductor industry.

Predistortion is a widely studied compensation method for transmitters in wireless communication [8], as well as RoF links [3]. To keep the RAUs as simple and cost-efficient as possible, the compensation of the RoF link (in the electrical domain) should be performed in the CU. That means predistortion should be used in downlink transmission and postdistortion in uplink transmission [9].

II/6

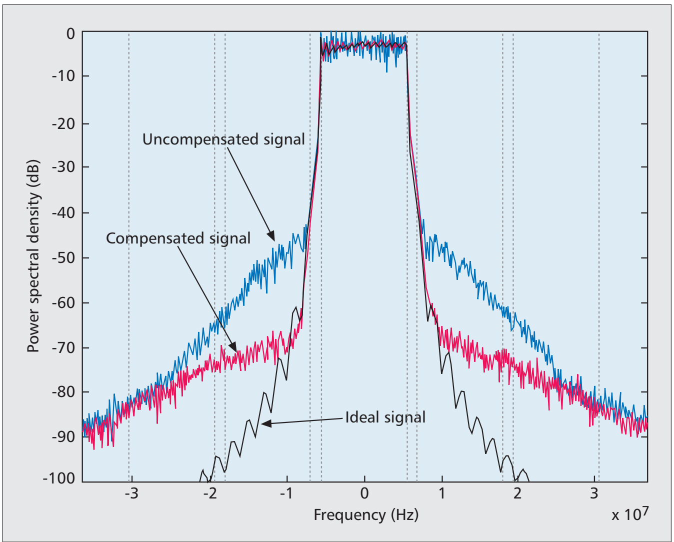


Figure 6. *Signal spectra at the output of the RoF link.*

Predistortion can be implemented by either digital or analog techniques. With digital predistortion we obtain an attractive solution for adaptive compensation, the control of adaptive algorithms and the predistorter easily handled by digital signal processing (DSP) in baseband. Although analog predistortion has been proposed to obtain low-cost compensation in an optical link [15], it is non-adaptive, more difficult to attain, and has smaller correction bandwidth. In a system that may require baseband digital signal processing (DSP) for virtual MIMO algorithms, for example, implementing the predistorter in DSP would seem to be advantageous.

Providing the feedback signal from the RAU to the CU is one of the challenging tasks in the adaptive compensation of the RoF link. This is due to possible nonlinearity of the feedback link; actually it can be as nonlinear as the RoF link, which is being compensated for. Here it is assumed that the nonlinear, uncompensated feedback connection would destroy the performance of the compensation, because the predistorter should ideally see only the non-idealities for which it tries to compensate. Therefore, an approach where the RoF link in the uplink direction is first compensated for using a postdistorter and known training signal from the RAU is used here (Fig. 1). After that the already compensated for uplink RoF link can be used as a feedback connection for the compensation of the RoF link in the downlink direction.

Here, the adaptive identification of the predistorter as well as postdistorter is done using an indirect learning architecture [8]. As the predistorter (and postdistorter) the polynomial structure is used. In this article we use adaptive algorithms presented in [16] where more detailed discussions on the algorithms and their complexity can be found.

A significant reduction of spectral regrowth using the predistortion with the proposed algorithms can be seen in Fig. 6, where the signal spectrum at the output of the compensated RoF link using OFDM signals with 256 subcarriers is shown. The spectra of the uncompensated and ideal signals are also shown in the figure. As discussed earlier, the compensated UL RoF link is used as the feedback. Comparing the results with an ideal feedback, any difference of the spectra cannot be seen. However, it is observed that with an ideal feedback, the error signal of the adaptation is a little smaller.

Using the recursive least squares (RLS) solution, the convergence of the adaptation is achieved very quickly. To achieve the same performance with the proposed LMS algorithm, about eight times more iterations are needed. On the other hand, the RLS is much more complex than the LMS. Therefore, we propose to use the combination of the RLS and LMS, where the first iteration cycle is done using the RLS and then after its convergence, a tracking mode is turned on using the LMS. Thus, fast convergence and low complexity in the tracking mode can be achieved. With memory effects, the compensation becomes even more difficult using the LMS, at least from the convergence speed point of view. The RLS solution seems to be more robust for the memory effects. For more information, see the compensation for the memoryless RoF link and power amplifier with memory connected in series in [9].

Considering the inband distortions, a noticeable improvement of EVM performance is achieved using the predistortion. Using, for example, the OFDM signal with 1024-QAM, the average EVM when the algorithm is converged is about 0.06 percent, which is considerably less than the EVM of the uncompensated signal.

Conclusions

Wireless communication systems clearly benefit by exploiting distributed antennas. In fact, in addition to increasing the supported data rate and optimizing the resource allocation procedure, distributed antennas improve the handling and management of handovers and interference between users. The distributed antennas are connected to a central unit by RoF links. RoF is a simple-to-implement solution considered key to developing cost-efficient DAS. In this article we analyze and discuss the deleterious effects of delays introduced in the DAS architecture. Moreover, using the proposed model for RoF links, we analyze how nonlinearities affect the BER, EVM, and spectral regrowth. Finally, in order to make the proposed concept truly implementable, we propose and investigate compensation approaches for these impairments.

Our analysis shows that the delay effects need to be taken into account, and compensated for as well, to guarantee the reasonable operations of the virtual MIMO algorithms. Moreover, the results show that the inband distortions are not critical; for example, only with large constellations can we observe remarkable BER degradation due to the nonlinearities. On the other hand, out-of-band distortions are more severe. Using the predistortion approach, significant reduction of the inband as well as out-of-band distortions can be achieved.

It can be seen from the results that the RoF nonlinearities increase the EVM in the single link. However, we saw that the low BER was obtained with challenging 1024-QAM. Therefore, it can be predicted that the nonlinear effects will not prevent the use of virtual MIMO techniques in the DAS where the RAUs are connected to the CU via RoF, especially if these nonlinear effects are compensated. However, some system parameters such as cyclic prefix length and guard time between the UL and DL transmission periods have to be adjusted to take into account the additional propagation delay caused by the optical transportation of the signal.

ACKNOWLEDGMENTS

A. Hekkala would like to thank Prof. M. Katz, CWC, Finland, for valuable discussions during the work.

REFERENCES

[1] FUTON project, "Fibre Optic Networks for Distributed, Extendible Heterogeneous Radio Architectures and Service Provisioning," ICT-2007-215533; http://www.ict-futon.eu/

[2] C. H. Cox III, *Analog Optical Links: Theory and Practice*, Cambridge Univ. Press, 2004.

[3] X. N. Fernando and A. B. Sesay, "Adaptive Asymmetric Linearization of Radio over Fiber Links for Wireless Access," *IEEE Trans. Vehic. Tech.*, Nov. 2002, pp. 1576–86.

[4] S. Pato, J. Pedro, and P. Monteiro, "Comparative Evaluation of Fibre-Optic Architectures for Next-Generation Distributed Antenna Systems," *11th Int'l. Conf. Transparent Optical Net.*, Azores, Portugal, June 2009.

[5] D. Wake *et al.*, "A Comparison of Remote Radio Head Optical Transmission Technologies for Next Generation Wireless Systems," *IEEE Photonics Soc. Annual Mtg.*, Belek-Antalya, Turkey, Oct. 2009.

[6] D. Wake, A. Nkansah, and N. J. Gomes, "Radio over Fiber Link Design for Next Generation Wireless Systems," *IEEE/OSA J. Lightwave Tech.*, submitted for publication.

[7] G. Fettweis *et al.*, "Dirty RF: A New Paradigm," *Int'l. J. Wireless Info. Net.*, vol. 14, June 2007, pp. 133–48.

[8] L. Ding *et al.*, "A Robust Digital Baseband Predistorter Constructed using Memory Polynomials," *IEEE Trans. Commun.*, vol. 52. Jan. 2004, pp. 159–65.

[9] A. Hekkala *et al.*, "Architectures for Joint Compensation of RoF and PA with Nonideal Feedback," *IEEE VTC-Spring*, Taipei, Taiwan, May 2010.

[10] V. Kotzsch and G. Fettweis, "Interference Analysis in Time and Frequency Asynchronous Network MIMO OFDM Systems," *IEEE WCNC*, Sydney, Australia, Apr. 2010.

[11] I. Harjula *et al.*, "Practical Issues in the Combining of MIMO Techniques and RoF in OFDM/A Systems," *WSEAS Int'l. Conf. Electronics, Hardware, Wireless, Optical Commun.*, Cambridge, U.K., Feb. 2008.

[12] J. Liu *et al.*, "Impact and Mitigation of Multiantenna Analog Front-End Mismatch in Transmit Maximum Ration Combining," *EURASIP J. Applied Signal Process.*, vol. 2006, 2006, pp. 1–14.

[13] H. Kim *et al.*, "Radio-over-Fiber System for TDD-Based OFDMA Wireless Communication Systems," *IEEE/OSA J. Lightwave Tech.*, vol. 25, Nov. 2007, pp. 1–9.

[14] J. G. Proakis, *Digital Communications*, 3rd ed., McGraw-Hill, 1995.

[15] L. Roselli *et al.*, "Analog Laser Predistortion for Multiservice Radio-over-Fiber Systems," *IEEE/OSA J. Lightwave Tech.*, vol. 21, May 2003, pp. 1211–23.

[16] A. Hekkala and M. Lasanen, "Performance of Adaptive Algorithms for Compensation of Radio over Fiber Links," *IEEE Wireless Telecommun. Symp.*, Prague, Czech Republic, Apr. 2009.

BIOGRAPHIES

ATSO HEKKALA (atso.hekkala@vtt.fi) received his M.Sc. in electrical engineering from the University of Oulu, Finland, in 2002. From 2002 to 2004 he was with the Centre for Wireless Communications at the University of Oulu. In 2004 he joined VTT Technical Research Centre of Finland in Oulu as a research scientist. He is also a Ph.D. student at the University of Oulu. His current research interests include compensation for nonlinear transmitters in distributed antenna systems, adaptive signal processing, and cognitive radios.

MIKA LASANEN received his M.Sc. in electrical engineering from the University of Oulu in 1998. Since then he has worked for VTT as a research scientist and project manager. His current research topics are related to transmitter impairment compensation techniques and synchronization issues in distributed antenna systems.

ILKKA HARJULA received his M.Sc. degree and Lic.Sc. degree in Electrical Engineering from the University of Oulu in 2002 and 2008, respectively. Since 2002, he has been working at VTT Technical Research Centre of Finland as a research scientist. His research work has covered various topics on the physical layer with various system models, and he has acted as an advisor for several Master's theses. His research interests lay in estimation theory and MIMO algorithms, especially tailored for OFDMA systems.

LUIS C. VIEIRA received his B.Eng. degree in electrical engineering from Universidade Federal de Santa Maria, Brazil, in 1992, his postgraduate Diploma in telecommunications system engineering from Instituto Nacional de Telecomunicações, Brazil, in 1998, and his M.Sc. degree in electrical engineering and industrial informatics from Centro Federal de Educação Tecnológica do Paraná, Brazil in 2003. He is currently working toward his Ph.D. degree in electronic engineering at the University of Kent, United Kingdom, on leave from Federal University of Technology — Paraná, Brazil, where he holds a lecturer position in Telecommunications. His present research interests include modeling and linearization of radio over fiber systems.

NATHAN J. GOMES [M'92, SM'06] received his B.Sc. degree from the University of Sussex, United Kingdom, in 1984 and his Ph.D. degree from University College London in 1988, both in electronic engineering. From 1988 to 1989 he held a Royal Society European Exchange Fellowship at ENST, Paris. Since late 1989, he has been at the University of Kent, where he is now a reader in broadband communications. His present research interests include radio over fiber systems and networks, the photonic generation and transport of millimeter-wave signals, and photoreceivers for such applications.

ANTHONY NKANSAH received his B.Eng. (with honors) degree in electronic engineering, his M.Sc. degree in broadband and mobile communication networks, and his Ph.D. degree in electronic engineering from the University of Kent in 2000, 2001, and 2007, respectively. His research interests include low-cost microwave and millimeter-wave radio over fiber networks and their deployment within premises.

STEFFEN BITTNER received his Dipl-Ing. degree in 2005 and his Ph.D. degree in 2009 both from Technische Universität Dresden, Germany. From 1999 until 2005 he studied electrical engineering at TU Dresden, where he specialized in mobile communication. He was a participant in the European exchange program ERASMUS 2003/2004 where he studied at the University of Surrey, Guildford, United Kingdom. In 2004 he was with the R&D Administration at Asahi Kasei Corporation, Atsugi, Japan. Since 2005 he has been a member of the Vodafone Chair Mobile Communications Systems, currently doing research in the fields of dirty RF, MIMO, smart antennas, and channel coding.

FABIAN DIEHM received his diploma (Dipl.-Ing.) degree in information systems engineering from Dresden University of Technology with honors in 2009. Currently, he is with the Vodafone Chair Mobile Communications Systems at Dresden University of Technology, where he is working toward his Ph.D. degree in communications. His research interests include cooperative multipoint (CoMP) techniques under real-world constraints and scheduling for cooperative multicell networks.

VINCENT KOTZSCH received his Dipl.-Ing. (FH) in computer and automation technology from the University of Applied Sciences Dresden in 2004 and his M.Sc. in communication and information technology from Dresden University of Technology in 2007. Currently, he is with the Vodafone Chair Mobile Communications Systems at Dresden University of Technology, where he is working toward his Ph.D. degree in communications. His research interests include multicell multi-user joint detection and transmission, as well as synchronization in distributed antenna systems.

Some system parameters such as cyclic prefix length and guard time between the UL and DL transmission periods have to be adjusted to take into account the additional propagation delay caused by the optical transportation of the signal.

PAPER III

Architectures for joint compensation of RoF and PA with nonideal feedback

In: Proceedings of IEEE Vehicular Technology Conference (VTC Spring), Taipei, Taiwan, May 2010, pp. 1–5.

Architectures for Joint Compensation of RoF and PA with Nonideal Feedback

Atso Hekkala and Mika Lasanen
VTT Technical Research Centre of Finland
P.O. Box 1100, FI-90571 Oulu, Finland
atso.hekkala@vtt.fi

Luis C. Vieira, Nathan J. Gomes, and Anthony Nkansah
Department of Electronics - University of Kent
Canterbury, Kent, CT2 7NT, UK
lcv3@kent.ac.uk

***Abstract*—A high capacity wireless communication system requires careful design to minimize interference and distortion effects. This paper considers the adaptive predistortion of the nonlinear distortions induced by a Radio over Fiber (RoF) link and power amplifier (PA) connected in series. In particular, we study the architectures for the joint compensation of the nonlinearities in the presence of nonideal feedback. From the adaptive algorithm point of view, we study different combinations of algorithms for the predistortion. Our simulation results indicate that combined use of least mean squares (LMS) and recursive least squares (RLS) gives the best trade-off between complexity and performance. In addition, we show that the use of nonideal feedback causes a collapse in the performance of the predistortion. However, when using a compensated RoF link for feedback, the degradation of the adjacent channel power is very small compared to the case of the ideal feedback.**

Keywords-adaptive predistortion, LMS, power amplifier, Radio over Fiber, RLS

I. INTRODUCTION

Great expectations exist for International Mobile Telecommunication –Advanced (IMT-A) systems in terms of data rates. This requires exploiting several advanced techniques such as multiple-input multiple-output (MIMO) processing with spectrally efficient linear modulation techniques, e.g. orthogonal frequency division multiplexing (OFDM). These techniques are very sensitive to nonlinear distortions. Due to high capacity requirements, small cells are needed in a cellular architecture. Interference between neighboring users and frequent handovers limit the increase of the system capacity. In addition, a large number of conventional basestations becomes expensive.

A distributed antenna system (DAS) has been introduced as an elegant solution for the challenges, see e.g. [1], [2]. In the DAS, conventional basestations can be replaced by simple Remote Antenna Units (RAUs) connected via optical fibers, i.e. Radio over Fiber (RoF) links, to a Central Unit (CU). Almost all the signal processing can be centralized to the CU allowing the RAUs to be as simple and inexpensive as possible [2]. The DAS enables centralized processing with perfect cooperation between the RAUs. In addition, handovers and inter-cell interference mitigation are handled more easily by the CU via a RoF network.

Optical fiber technology is the obvious solution to construct the required transparent interconnections between the RAUs and CUs. Optical fibers have benefits of low attenuation and enormous bandwidth. In particular, RoF technology can lead to simple, inexpensive antenna units [1], [2], important in the proposed DAS. However, nonlinear distortions experienced in the various cost-efficient devices may be one of the major problems in these RoF links [3]. In addition, a power amplifier (PA) is required in the RAU although the requirements may be less demanding for RAUs in a DAS than for solitary, high-power base stations. The PA is also a nonlinear component of which usage requires tradeoffs in terms of efficiency and linearity. When both the nonlinear RoF link and the PA are taken into account, the nonlinearity phenomenon is even more complicated.

Amplitude-to-amplitude (AM/AM) and amplitude-to-phase (AM/PM) models have been applied to simulate the nonlinear distortions of RoF links, see e.g. [4], [5]. In this black-box modeling approach, the nonlinear effects of the link are observed when the input RF power is varied, that is, the nonlinear amplitude and phase characteristics are obtained from the input-output measured data.

Due to its simplicity and general ease of implementation, predistortion has been widely used to compensate the RoF link or PA nonlinearity, see e.g. [3], [5], and [6]. However, a joint compensation of both has not been considered in the literature.

In this paper, we study the architectures for the joint compensation of the RoF link and the PA connected in series. In particular, we study two options for the feedback connection from the RAU. In addition, to the best of authors' knowledge, this is the first study on the predistortion of the RoF link and PA with a nonideal feedback connection. For adaptations, we utilize two adaptive algorithms, namely least mean squares (LMS) and recursive least squares (RLS). From the algorithm point of view, we study different combinations of the algorithms for the predistortion. This work is an extension of [7] where we studied the performance of the different adaptive algorithms for the compensation of the RoF link.

The rest of the paper is organized as follows. In Section II, we introduce the system model. Then, we discuss the compensation architectures in Section III. In Section IV, we show simulation results for the compensation of the RAU and PA connected in series. Finally, Section V states the main conclusions to be drawn.

II. SYSTEM DESCRIPTION

The simplified block diagram of the system model is depicted in Fig. 1. An input signal is fed to a digital predistorter, which compensates nonlinearities introduced in a

This work has been performed in the framework of the FUTON FP7 ICT-2007-215533 project, which is partially funded by the European Community.

L. C. Vieira, lecturer at UTFPR and PhD student at the University of Kent, is sponsored by the Brazilian Government through CNPq and UTFPR, whose support is gratefully acknowledged.

978-1-4244-2519-8/10/$26.00 ©2010 IEEE

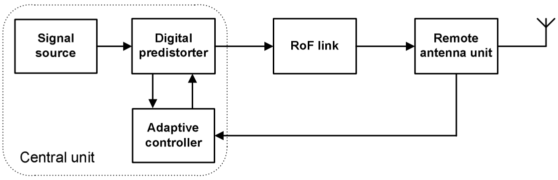


Figure 1. Block diagram of the simplified system model.

RoF link and a PA in the RAU. An adaptive controller determines the parameters of the digital predistorter by comparing a feedback signal from the RAU with a reference signal, i.e. the original input signal.

We utilize complex baseband modeling using a sampling frequency of 76.8 MHz. When constructing the signal model, we follow closely the specifications defined in [8]. The used sampling frequency limits the useful bandwidth of the OFDM signal in our study. Keeping in mind that for predistortion we want to utilize (at least) third or fifth order nonlinear terms of the signal, the maximum useful signal bandwidth is limited to 15 MHz. That means, in this work, an OFDM signal having 256 subcarriers, which corresponds to 12.5 MHz signal bandwidth, is used.

To reduce peak-to-average power ratio to 8 dB, we can optionally apply clipping to the generated signal. We use adjacent channel powers (ACPs) and adaptation errors as performance measures.

In this work, we use the AM/AM and AM/PM characteristics to model and simulate the RoF link, see Fig. 2. We extract the model from an experimental directly modulated laser optical link consisting of a 1500-nm distributed feedback laser from Alcatel-Thales III-V Labs, an optical patch cord and a PIN photodiode (Appointech). A 1 GHz excitation signal was applied by a Vector Network Analyzer, and we measure the output power and phase shift after the optical link, with the input power varied in order to find the saturation region of the laser. We calibrate the experimental setup against the response of the RF cables and amplifier used, which is needed to achieve the dynamic range of 12 dB for this characterization.

Based on the measurements, we model the AM/AM and AM/PM conversions by the functions $g(A)$ and $\Phi(A)$, respectively, as follows:

$$g(A) = \frac{m_1 A^3 + m_2 A^2 + m_3 A}{A^3 + n_1 A^2 + n_2 A + n_3} \quad (1)$$

$$\Phi(A) = \frac{p_1 A^4 + p_2 A^3 + p_3 A^2 + p_4 A + p_5}{A^2 + q_1 A + q_2} \quad (2)$$

where A is the input amplitude. The coefficients for (1) and (2) are given in TABLE I. The input amplitude in (2) is normalized by mean 4.309 and standard deviation 1.704. We fit these models in Matlab using a Levenberg-Marquardt algorithm for the AM/AM and Trust-Region algorithm for the AM/PM. The root mean squared errors (RMSE) of the

TABLE I. COEFFICIENTS FOR AM/AM AND AM/PM MODELS OF THE ROF LINK.

Coefficients for AM/AM model at 1 GHz			
m_1	16.22	n_1	952.3
m_2	-287.6	n_2	-1.597e004
m_3	1504	n_3	7.965e004
Coefficients for AM/PM model at 1 GHz			
p_1	-0.2494	q_1	-2.443
p_2	-0.04929	q_1	2.255
p_3	61.49		
p_4	-149.8		
p_5	138.3		

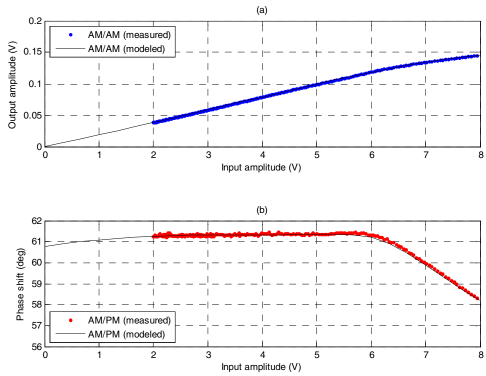


Figure 2. AM/AM (a) and AM/PM (b) characteristics of the RoF model.

AM/AM and AM/PM fits are 0.000199 and 0.021770, respectively.

In this work, we use the model of the nonlinear PA developed in [6]. The measurements for the model were carried out using a three-carrier wideband code division multiple access (WCDMA) signal having total bandwidth of 15 MHz. Coefficients for the model were extracted from an actual class AB PA. The memory polynomial model for PA nonlinearities can be given by [6]

$$y(n) = \sum_{k=1}^{K} \sum_{q=0}^{Q} c_{kq} z(n-q) \left| z(n-q) \right|^{k-1}, k = 1, 3, 5, \ldots \quad (3)$$

where K is the nonlinearity order, Q is the length of the memory, $z(n)$ and $y(n)$ are the input and output signals of the model, respectively. The coefficients c_{kq} are shown in TABLE II. To clarify the memory effects of the model, the AM/AM and AM/PM characteristics are shown in Fig. 3 (using the OFDM signal with clipping).

In this work, we use adaptive algorithms we introduced in [7]. The LMS algorithm was extended by applying scaled step sizes to the LMS adaptation for the nonlinear polynomial predistorter. The modified LMS algorithm can be given by

$$\begin{aligned} \mathbf{w}(n+1) &= \mathbf{w}(n) + \boldsymbol{\mu}_{\mathrm{LMS}} e^*(n)\mathbf{u}(n) \\ e(n) &= z(n) - \mathbf{w}^{\mathrm{H}}(n)\mathbf{u}(n) \end{aligned} \quad (4)$$

TABLE II. COEFFICIENTS FOR THE PA MODEL.

c_{10} 1.0513 + 0.0904*j*	c_{30} -0.0542 – 0.2900*j*	c_{50} -0.9657 – 0.7028*j*
c_{11} -0.0680 – 0.0023*j*	c_{31} 0.2234 + 0.2317*j*	c_{51} -0.2451 – 0.3735*j*
c_{12} 0.0289 – 0.0054*j*	c_{32} -0.0621 – 00932*j*	c_{52} 0.1229 + 0.1508*j*

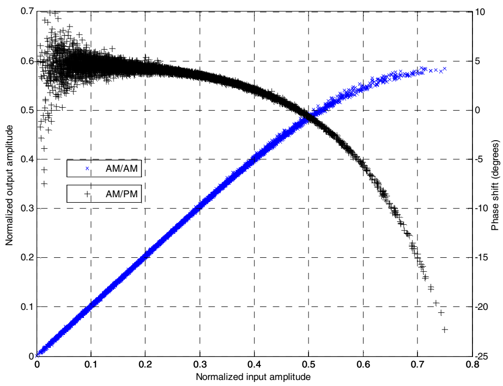


Figure 3. AM/AM and AM/PM characteristics of the PA model.

where $[\cdot]^H$ denotes Hermitian transpose, $[\cdot]^*$ denotes complex conjugate, $\mathbf{w}(n)$ is the filter weight vector, and $z(n)$ represents the desired signal. The normalized feedback signal for the adaptation $\mathbf{u}(n)$ and the normalized step size $\boldsymbol{\mu}_{\mathrm{LMS}}$ are defined by

$$\begin{aligned} \mathbf{u}(n) &= \left[u_1(n) \;\; u_2(n) \;\; \ldots \;\; u_k(n) \;\; \ldots \;\; u_K(n)\right]^{\mathrm{T}} \\ \boldsymbol{\mu}_{\mathrm{LMS}} &= \mu_{LMS} \operatorname{diag}\left[\left(\sigma_1^2\right)^{-1} \;\; \ldots \;\; \left(\sigma_k^2\right)^{-1} \;\; \ldots \;\; \left(\sigma_K^2\right)^{-1}\right] \end{aligned} \tag{5}$$

where $\sigma_k^2 = \frac{1}{N}\sum_{n=1}^{N}\left|u_k(n)\right|^2$, $u_k(n) = y(n)|y(n)|^{k-1}$ ($y(n)$ as a feedback signal), μ_{LMS} is the step size, $[\cdot]^T$ denotes matrix transpose, and N is the number of the samples in a signal block. In the adaptations, we also use the RLS solution [9]. See more detailed discussions on the algorithms and their complexity in [7].

For the compensation of the nonlinearities, we use an adaptive predistorter structure based on the memory polynomials. The predistorter and the adaptation of it utilized in this work are reported in [7].

III. COMPENSATION ARCHITECTURE

Our scenario is to perform the compensation for the downlink (DL) RoF link and the PA connected in series. Fig. 4 depicts the more detailed block diagram of the compensation approaches showing two options for the feedback connections from the RAU to the CU. In more detail, in the first feedback option, we have the feedback connection only after the PA, i.e. we compensate both the DL RoF link and the PA simultaneously. The second option is divided into two consecutive phases. First, we take the feedback before the PA,

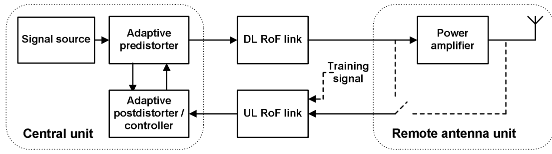


Figure 4. Block diagram of the system model showing more detailed feedback connection.

i.e. we compensate only the DL RoF link. After the compensation of the DL RoF link is performed, we change the feedback connection after the PA using the switch shown in Fig. 4. Now, because the predistorter ideally sees only the nonlinearity of the PA, we can easily compensate the PA. Thus, both the DL RoF link and the PA are being compensated.

In the first option, there are two nonlinear blocks, i.e. the DL RoF link and the PA, connected in series to be compensated simultaneously by one predistorter. We assume that two nonlinearities connected in series increase the degree of the nonlinearity of the whole system by summation. It is intuitively understandable by substituting $g(A)$ from (1) to $z(n)$ in (3). In addition, the memory elements of the PA model after the RoF nonlinearities can cause unexpected and difficult to analyze behavior of the signal. These may affect, at least, the required predistorter order. Hence, with a reasonable order of the predistorter, the performance of the compensation may not sufficient.

In the second option, i.e. in the consecutive compensation, two predistorters in the CU and two feedback connections in the RAU, i.e. before and after PA, are needed.

The complexity comparison between these two options is not straightforward. The consecutive compensation seems more complex than the simultaneous compensation scheme in terms of the number of the predistorters. However, in the consecutive compensation scheme, the actual predistorters may have lower complexity as the required nonlinearity order may differ between the approaches. In addition, the adaptation block may dominate the complexity of both schemes and its maximum nonlinearity order may be critical for an implementation. Finally, in both cases only one adaptation block is needed at a time.

In addition to the DL RoF link, we also consider an uplink (UL) RoF link as a nonideal feedback loop for the adaptive predistortion. Fig. 4 shows the DL RoF link in the upper signal branch and the UL RoF link in the lower signal branch.

If we assume that the use of the uncompensated UL RoF link will cause a collapse in the performance, we need first to compensate the UL RoF link using a known training signal and a postdistortion. Then we can use the compensated UL RoF link as the feedback for the compensation in the DL direction. For the UL compensation, we use the RLS solution due to its fast convergence. Then, in the training of the predistorter in the DL direction, we can use the same postdistorter training block as used in the UL direction.

IV. RESULTS

In the training of the predistorters, each iteration uses a signal block of 4000 samples and the predistorter is updated after each signal block. For more details, see [7].

In the simulations, the feedback connection is assumed ideal or the UL RoF link is used as the feedback connection. The UL RoF link is measured and modeled in the same way as discussed in Section II, but using a 600 MHz signal. The parameters are not shown here due to space limitations. The compensated UL RoF link is achieved by one iteration using RLS solution.

When showing adjacent channel powers (ACPs) in decibels relative to the carrier power, we calculate the average value of the lower and higher ACP, i.e. the channels centered at -12.5 and +12.5 MHz, as indicated in Fig. 5. Adaptation error calculates the difference between desired and distorted signals in decibels averaged over the whole adaptation signal block of 4000 samples.

We noticed, that a larger number than 5 as the predistorter order gives only very little further improvement to ACP. In addition, we use only odd order nonlinear terms for the predistorter. Due to the memoryless characteristic of the RoF model, we can use the memoryless predistorter for its compensation, i.e. the memory length Q is set to zero. On the other hand, for the PA and the joint compensation, the predistorter with memory is needed. In these cases Q is set to 2.

Signal spectra at the output of compensated and uncompensated RoF and PA link is shown in Fig. 5. The spectrum of the input signal is shown as well. The compensation is done using the simultaneous compensation with the RLS solution. After one iteration, an ACP of -55 dB is achieved.

Using the LMS it takes about 40 iterations to achieve the convergence and an ACP of -53 dB, i.e. almost the same ACP as using the RLS. However, in terms of the error, the difference is large as can be seen in Fig. 6 where the errors and ACPs after the PA using the simultaneous compensation are shown. The step size for the LMS is empirically selected so that the maximum speed of the convergence is achieved. We use the LMS step size of $\mu_{LMS} = 0.002$.

In the RLS + LMS combination, only the first iteration is done using the RLS and then, a tracking mode with the LMS is turned on. Using this combination of the algorithms, fast convergence and low complexity after it is achieved. Together with lower complexity, lower energy consumption is obtained than when using the RLS alone. To obtain benefits in practical implementations, the RLS may be dedicated to the calibration of the systems, and the LMS may be used during data transmission for tracking or fine tuning. Note that this combination gives the same performance as the use of the RLS also in the tracking mode but with lower algorithmic complexity which directly influences energy consumption.

The errors and ACPs using the consecutive compensation are shown in Fig. 7. Now, the RLS + LMS combination means that the first iteration for the RoF is done using the RLS, then the next one for the compensated RoF + PA also uses RLS. After that the tracking mode with the LMS is turned on. The convergence is achieved after the RLS iterations. Using only the LMS, it takes 10 iterations to converge in the RoF compensation. After that, to achieve the convergence in the compensated RoF + PA compensation, about 30 iterations are needed. Finally, the adaptation error in the LMS is about 10 dB worse than in the RLS + LMS case. However, the ACPs are almost the same. Note, that using LMS, the first 10 ACP values

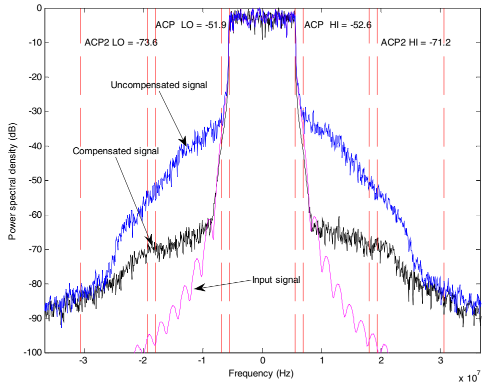


Figure 5. Spectra of input, uncompensated, and compensated signal.

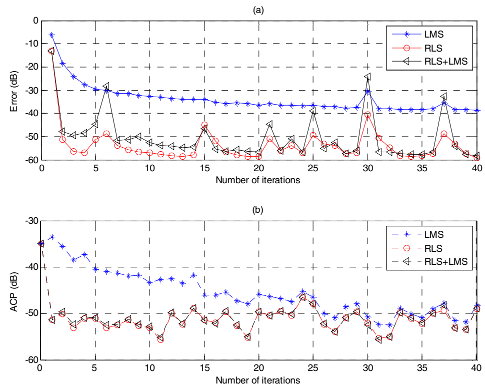


Figure 6. Errors (a) and ACPs (b) after PA using simultaneous compensation.

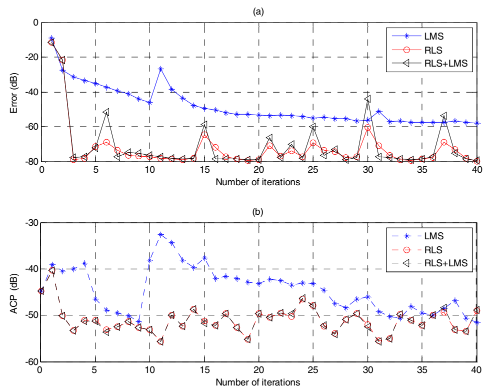


Figure 7. Errors (a) and ACPs (b) using consecutive compensation.

in Fig. 7 are measured after the RoF link. For the RoF compensation, we set the LMS step size to 0.006 and for the compensated RoF + PA, it is set to 0.002.

Comparing the results in Figs. 6 and 7, we see that the both methods give comparable performance in terms of ACP. However, with the consecutive compensation, about 20 dB lower adaptation error level is achieved. It seems that in our system model, it is too difficult to compensate the nonlinearities connected in series for one predistorter. Due to lower adaptation error, we assume the consecutive method has the potential to compensate more difficult nonlinearities. In addition, larger error may more severely affect in-band distortions such as error vector magnitude or bit error rate. We leave the study of the in-band distortions for future work.

To study nonideal feedback effects, short tests using simultaneous compensation with the uncompensated UL RoF link as the feedback were carried out. As expected, the performance was not good. Only a minor improvement over the uncompensated ACPs was obtained. That is because the predistorter tries to compensate, in addition to the PA, both the DL and UL RoF links. The results are not shown due to space limitations.

The adaptation errors and ACPs in the presence of the compensated UL RoF link as the feedback are shown in Fig. 8. In both the simultaneous and consecutive compensation schemes the combination of the RLS + LMS is used. We see a similar behavior with earlier results, i.e. the ACPs are the same for both options, but the adaptation error is smaller using consecutive compensation. The LMS step sizes are the same as in the earlier cases.

Comparing the results shown in Figs. 6, 7, and 8, we notice some degradation of the performance due to the nonideal feedback. In the presence of the nonideal feedback, we achieve about 10 dB worse adaptation errors than in the case of ideal feedback. On the other hand, the ACP degradations are very small.

V. Conclusion

In this work, we studied the adaptive predistortion of the nonlinear distortions induced by an RoF link and a power amplifier connected in series. We introduced and compared two architectures for the joint compensation of the nonlinearities in the presence of nonideal feedback. From the adaptive algorithm point of view, we studied different combination of the algorithms for the predistortion.

The best performances are achieved using the consecutive compensation scheme. In addition, using the compensated UL RoF link as the feedback, the degradation of the ACPs is very small compared to the case of the ideal feedback. On the other hand, the use of uncompensated nonideal feedback causes a collapse in the performance of the predistortion.

Acknowledgement

A. Hekkala would like to thank I. Harjula, VTT, Finland, for valuable discussions during the work. The authors are also grateful to Alcatel-Thales III-V Lab (especially Frederic van Dijk) for the supply of the DFB laser modeled.

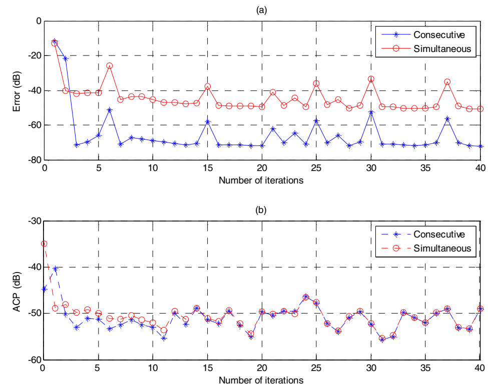


Figure 8. Errors (a) and ACPs (b) with nonideal feedback.

References

[1] H. Al-Raweshidy and S. Komaki, Eds., *Radio over Fiber Technologies for Mobile Communications Networks*. Norwood MA: Artech House, 2002.

[2] Fibre optic networks for distributed, extendible heterogeneous radio architectures and service provisioning. FUTON project. [Online]. Available: http://www.ict-futon.eu/.

[3] A. R. Shah and B. Jalali, "Adaptive equalisation for broadband predistortion linearisation of optical transmitters," in *Proc. Inst. Electr. Eng.-Optoelectron.*, vol. 152, pp. 16-32, Feb. 2005.

[4] Chin Hee Lee, V. Postoyalko and T. O'Farrell, "Analysis and simulation of AM-AM/PM nonlinear distortion due to direct laser modulation in radio over fibre systems," *Microwave Photonics, 2002. International Topical Meeting on*, pp. 137-140, 2002.

[5] X. N. Fernando and A. B. Sesay, "Adaptive asymmetric linearization of radio over fiber links for wireless access," *IEEE Trans. Vehic. Tech.*, vol. 51, pp. 1576-1586, Nov. 2002.

[6] L. Ding et al, "A robust digital baseband predistorter constructed using memory polynomials," *IEEE Trans. Commun.*, vol. 52, pp. 159-165, Jan. 2004.

[7] A. Hekkala and M. Lasanen, "Performance of adaptive algorithms for compensation of radio over fiber link," in *Proc. IEEE Wireless Telecomm. Symp.*, Apr. 2009.

[8] "D6.13.7 Test Scenarios and Calibration Cases Issue 2," IST-4-027756 WINNER II, Tech. Rep., Dec. 2006.

[9] S. Haykin, *Adaptive Filter Theory*. 4th ed., Upper Saddle River, NJ: Prentice Hall, 2002, Ch. 9.

PAPER IV

Predistortion of radio over fiber links: algorithms, implementation, and measurements

In: IEEE Transactions on Circuits and Systems–I: Regular Papers, Vol. 59, No. 3, pp. 664–672.

Predistortion of Radio Over Fiber Links: Algorithms, Implementation, and Measurements

Atso Hekkala, *Member, IEEE*, Mikko Hiivala, Mika Lasanen, Jari Perttu, Luis C. Vieira, *Graduate Student Member, IEEE*, Nathan J. Gomes, *Senior Member, IEEE*, and Anthony Nkansah

Abstract—**Distributed antenna systems (DASs) have been proposed for use in high-data-rate wireless communications. Connecting the central unit to remote antenna units, radio over fiber (RoF) links become essential parts of the DAS. One of the major problems in the RoF links is the nonlinear distortion experienced in its optoelectronic devices. This paper considers the adaptive compensation of the nonlinear RoF link. In particular, we present an extension to the conventional least-mean-square algorithm for memory-polynomial-based predistortion. In addition, we study different combinations of the algorithms for the predistortion. Moreover, we implement the adaptive predistorter in hardware, build a real RoF link, and verify the performance by measurements. The results demonstrate that distortion of the RoF link can be considerably diminished with a low complexity design.**

Index Terms—**Adaptive compensation, field programmable gate array (FPGA), least mean square (LMS), radio over fiber, recursive least squares (RLS).**

I. Introduction

DUE TO AN ever-increasing need for higher data rates in wireless communication, spectrally efficient modulation methods, e.g., orthogonal frequency-division multiplexing (OFDM), and multiple-input multiple-output (MIMO) techniques are required. On the other hand, in a cellular network, numerous conventional and expensive base stations are needed, and increased inter-cell-interference and handovers limit the capacity due to the need for small cells.

The concept of virtual MIMO, or a distributed antenna system (DAS), has been proposed as a solution to the above-mentioned problems, see, e.g., [1], [2]. In such a system, conventional base stations can be replaced by simple remote antenna units (RAUs) connected via optical fibers, i.e., radio over fiber (RoF) links, to a central unit (CU). Almost all the signal processing can be centralized in the CU, allowing the RAUs to be as simple and inexpensive as possible [2]. The DAS enables centralized processing with perfect cooperation between the RAUs. Handovers and inter-cell interference mitigation are handled more easily by the CU via a RoF network. Despite the RoF technology having benefits of low attenuation and enormous bandwidth, nonlinear distortion experienced in its optoelectronic devices may be one of the major problems in the RoF links [3].

Due to its simplicity and general ease of implementation, predistortion has been widely studied for the compensation of the nonlinearities stemming from the RoF links or power amplifiers, see, e.g., [4], [5] and references therein. For example, in [4], a memoryless polynomial predistorter is presented for RoF link compensation. The system model considers a single-carrier constant-envelope quadrature phase shift keying (QPSK) signal. For the adaptation in the model, a recursive least squares (RLS) solution is used—although such a solution would be challenging for practical systems in terms of complexity and numerical stability ([6], p. 659).

A low-complexity least-mean-square (LMS) algorithm has been widely studied for the identification and compensation of nonlinear systems, see, e.g., [7]–[12]. In [7], the use of the LMS algorithm is seen as inappropriate for nonlinear compensation because the convergence speed is extremely slow for higher-order nonlinearities. In [8], an adaptive Volterra filter based on the LMS algorithm is used for the control of a nonlinear noise process. The same step size for all nonlinear polynomial orders within one Volterra filter is used in that paper. In [9], [10], the LMS algorithm is used for the compensation of power amplifiers. In both papers, only one step size is used for all the nonlinearity orders in the algorithm.

In [11], when identifying a nonlinear Wiener system, the step size of the LMS algorithm is scaled according to the signal power. In addition, in [12], different LMS step sizes have been used for different polynomial orders in the predistorter. However, details of the step sizes or their descriptions are not given in [12].

A combination of using a software algorithm in a general purpose digital signal processor (DSP) for adapting the predistortion coefficients and a real-time hardware implementation on a field programmable gate array (FPGA) for the predistorter has been studied, e.g., in [13], [14], for implementing an adaptive predistorter for compensating power amplifier nonlinearity. The predistorters therein were based on the Volterra series and nonlinear auto-regressive moving average (NARMA) architectures, respectively.

In this paper, we study compensation of the nonlinear RoF link. In particular, we introduce adaptive algorithms for the predistorter. More specifically, we provide detail on how the LMS step sizes for different nonlinearity orders are scaled for the

Manuscript received February 07, 2011; revised May 12, 2011; accepted August 02, 2011. Date of publication October 20, 2011; date of current version February 24, 2012. This work was supported in the framework of the FUTON FP7 ICT-2007-215533 project, which is partially funded by the European Union. The work of A. Hekkala was supported by the Nokia Foundation. The work of L. C. Vieira was supported by the Brazilian Government through CNPq and UTFPR. Part of this paper was presented at the IEEE Wireless Telecommunications Symposium, Prague, Czech Republic, April 2009. This paper was recommended by Associate Editor M. Mondin.

A. Hekkala, M. Hiivala, M. Lasanen, and J. Perttu are with VTT Technical Research Centre of Finland, 90571 Oulu, Finland (e-mail: atso.hekkala@vtt.fi).

L. C. Vieira, N. J. Gomes, and A. Nkansah are with University of Kent, Canterbury, Kent, CT2 7NT, UK (e-mail: lcv3@kent.ac.uk).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TCSI.2011.2167267

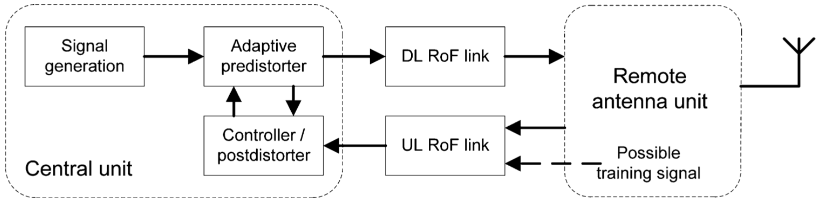


Fig. 1. Simplified block diagram of RoF link.

memory-polynomial-based predistortion. In addition, we study different combinations of the algorithms for the predistortion. To show the feasibility of our adaptive predistortion concept, we implement the adaptive predistorter in hardware, build a real RoF link, and verify the performance by measurements.

Part of this paper was presented in our earlier conference paper [15], where we introduced the idea of modifying the LMS algorithm. Preliminary results of the work have also been shown in [16] with off-line measurements, improving mainly static nonlinearity, showing only small EVM improvement. However, neither comparisons of the adaptive algorithms nor FPGA implementation were carried out in [16].

The predistortion performance strongly depends on the way that the nonlinear behavior of a device/link is observed and modeled. In our work, the experimental data are taken using an OFDM input signal with 64QAM (quadrature amplitude modulation) data, which represents a far more complex test signal than a single-carrier constant-envelope QPSK signal, for example. The high peak-to-average power ratio (PAPR) of the OFDM signal and the dynamic measurement technique used, allow us to capture both the static and dynamic RoF link nonlinearities. Thus, the predistorter is identified from a measurement setup that replicates very well real-application nonlinear link behavior. In addition, the predistortion performance is evaluated in real time using a FPGA-based predistorter preceding the RoF link.

The rest of the paper is organized as follows. In Section II, we introduce the system model and discuss the RoF technology and its fabrication and modeling. Then, we discuss the predistortion algorithms and architecture in Section III. In Section IV, we present the measurement setup and demonstrate the predistortion performance by measurements. Finally, Section V presents conclusions.

II. System Description

A. System Model

A simplified block diagram of the system model is depicted in Fig. 1, showing the compensation of the nonlinearities in the downlink (DL) direction and the possible use of the uplink (UL) RoF link as a feedback connection. An OFDM signal is generated in the CU and fed through a predistorter, which compensates distortion induced by the DL RoF link. From the RAU, the signal is transmitted over the air to the user. To implement adaptive compensation, a feedback signal is provided from the RAU back to the CU, e.g., through the UL RoF link. The coefficients of the adaptive predistorter are adjusted by a controller/postdistorter.

The OFDM signal consists of 115 data subcarriers and 13 zero subcarriers within an IFFT of size 128. The signal bandwidth is 6.25 MHz, with a sampling rate of 32 MHz. 64QAM data modulation is used. The OFDM signal is transmitted through the RoF link at an intermediate frequency (IF) of 50 MHz. When constructing the signal model, the specifications defined in [17] are closely followed.

Fig. 2. Internal picture of the laser module.

B. RoF System Description

In RoF technology, analog RF signals are transmitted transparently over a fiber distribution system. This type of signal transmission leads to simpler RAUs, and the analog signals generally occupy less bandwidth than their baseband equivalents. In addition, analog signal transmission is necessary in order to implement the joint processing of signals for the virtual MIMO system mentioned above. Transmission of digitized IF signals is also possible, but is not considered an economically feasible solution for high data rate wireless communications [18].

Direct modulation and external modulation are the most common modulation techniques used for RoF links. A single device—usually a distributed feedback (DFB) laser—serves both as the optical source and the RF/optical modulator for the direct modulation method, whereas an additional optical component is needed as modulator for the external modulation method, making this solution more expensive than direct modulation.

The nonlinear distortion in RoF links comes mainly from the optical modulation device [19]. However, the level of distortion in the output signal depends on the input signal amplitude and the modulation bandwidth. Chromatic dispersion of single-mode optical fibers for long links and saturation of photodiodes at high optical power may cause some nonlinear effects. However, using adequate link design and reasonable fiber

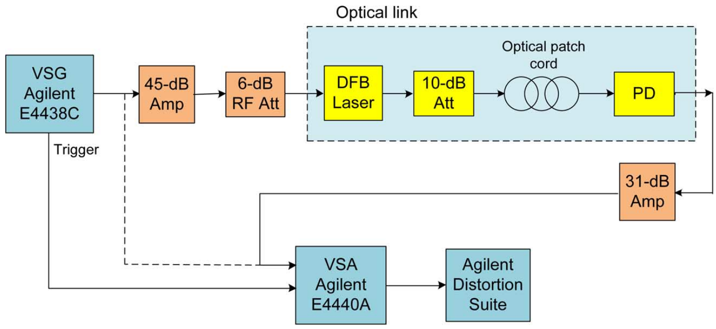


Fig. 3. Setup for testing and modeling the RoF link.

length, distortion from the fiber itself and the photodiode can be neglected.

In this work, a directly modulated RoF link is used for the experiments. The laser module consists of a Teradian uncooled DFB laser emitting at a wavelength of 1550 nm with an optical power of 5 dBm. It has a slope efficiency around 0.13 W/A, threshold current of 7 mA, and relaxation resonance around 3.5 GHz. The package includes a 30-dB isolator. A current source module is used to bias the laser at 31 mA through a surface mount bias tee and a resistor for impedance matching. All the components are mounted on a printed circuit board and enclosed in a metallic box for RF radiation shielding, as shown in Fig. 2. The RF signal from an external source is combined with the dc current from the current source to modulate the laser. The modulated optical signal is then launched into a single mode fiber (SMF) pigtail of 1-m length plus an optical attenuator of 10 dB, followed by a 1-m SMF patch cord to connect to the photodiode. The 10-dB attenuation replicates the expected loss from power splitters, connectors and fiber attenuation in the distribution network. As the fiber distances are relatively short and transmission frequencies are not high (in [2], the transmission at IF frequencies is proposed), dispersion is not considered to be a severe limitation in this work. The photodiode module consists of an Appointech PIN photodiode, with bandwidth of 2.5 GHz and responsivity of 1 A/W, mounted on a printed circuit board with a bias tee, and enclosed in a metallic box similar to the laser module.

The setup used for testing and modeling the RoF link is depicted in Fig. 3. Initially, the RoF link was tested using a single-tone input signal of 50 MHz with its power being swept from -10 to $+17$ dBm, there being found an optical link gain of -36.2 dB and a 1-dB compression point of $+14$ dBm. Then, a dynamic nonlinear modeling of the RoF link was performed using an OFDM input signal and, for the first time, a memory polynomial model [20]. In this approach, the memory polynomial model is obtained from measurements of the baseband input-output signals, using a time-domain measurement technique and a least-squares-based fitting algorithm. For the model extraction, the OFDM signal was downloaded into the Agilent E4438C vector signal generator (VSG), where the signal was modulated onto an RF carrier of 50 MHz and $+8.5$ dBm (at the laser input). The Agilent E4440A vector signal analyzer (VSA) was then connected to the VSG output in order to register its modulated signal as a reference for the modeling extraction. After that, the VSA was connected to the RoF link output, so that its response could be registered. The precise frequency and time alignment required to find the amplitude and phase distortion is accomplished by the digital signal processing code in the Agilent Distortion Suite software. The RoF memory polynomial model structure is the same as that used for the predistorter, as will be described in Section III, with its memory length (Q) set to 3 and the nonlinear order (K) set to 5. As a measure of the fitting accuracy, the normalized mean square error (NMSE) is used, which was computed as -37.83 dB. This model accuracy is close to the result reported in [20], considering the same Q and K parameters.

In order to align the input/output power levels at the RoF link with the power levels available from/to the measurement and prototyping platform (see Fig. 5) and drive the laser into its nonlinear operating region, two amplifiers and one RF attenuator are used, as shown in Fig. 3. The first amplifier, model Mini-Circuits ZHL-4240W, has a gain of 45 dB, with frequency range from 10 to 4200 MHz and 1-dB compression point (output) of $+27$ dBm. The VSG power was set to -30 dBm, which means 12 dB below the amplifier compression point. A 31-dB gain amplifier, model Mini-Circuits ZKL-2, is inserted after the photodiode with frequency range from 10 to 2000 MHz and 1-dB compression point (output) of $+15$ dBm. In the final predistortion experiments using the prototyping platform, input RF powers to the laser of 5 dBm and 8 dBm were used, corresponding to rms modulation depths of 39.2% and 55.4%, respectively. As these are OFDM signals with high PAPRs, the laser was clearly being driven below threshold.

III. Predistortion Algorithms and Architecture

For the compensation of the RoF link, a predistorter structure based on memory polynomials [21] is used. The predistorter output z is given by

$$z(n) = \sum_{k=1}^{K} \sum_{q=0}^{Q} c_{kq} x(n-q) |x(n-q)|^{k-1} \quad (1)$$

where x is the input signal, c_{kq} are the polynomial coefficients, and K and Q are the predistorter nonlinearity order and memory length, respectively. Equation (1) is a simplification of the Volterra series where only diagonal terms in the Volterra

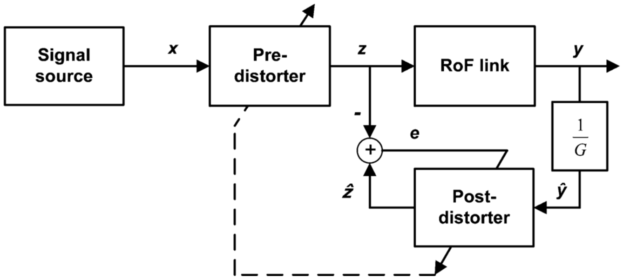


Fig. 4. Compensation using indirect learning architecture. Dashed line indicates the copying of the postdistorter to the predistorter after processing of input/output samples block.

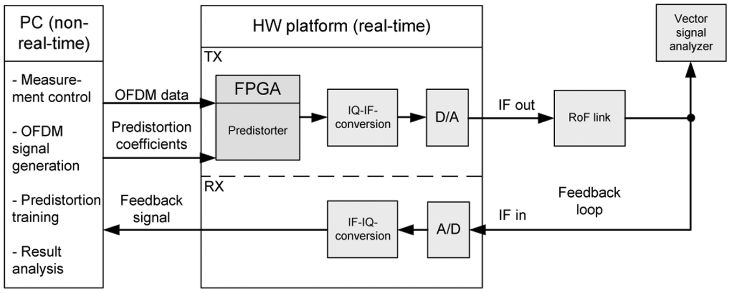


Fig. 5. Block diagram of the prototype environment.

kernels are included. In this work, we use only the odd-order nonlinear terms (i.e., $k = 1, 3, 5, \ldots$) in (1) in the predistorter because the hardware implementation is simpler. As a trade-off, a small performance degradation may result, see, e.g., [22].

The adaptive identification of the predistorter is performed using an indirect learning architecture [21], which is a form of nonlinear adaptive inverse control (see the block diagram in Fig. 4). In this architecture, the predistorter-training block, i.e., the postdistorter, is driven by the normalized output of the RoF link and the predistorter output. In order to achieve the inverse of the RoF link, the postdistorter block adjusts its parameters using an adaptive optimization algorithm. After processing a block of, say, 4000 input/output samples, the inverse model, i.e., the postdistorter, is directly used as the predistorter.

It is well known that the nonlinear characteristics of the RoF link vary in time due to thermal effects and ageing of the components, etc. However, such variations occur slowly. Therefore, we assume that real-time processing in the adaptation is not needed. In this work, the adaptation is performed off-line using stored signals. This makes it possible to consider floating-point arithmetic, enabling maximum accuracy. A practical implementation could be done with a digital signal processor (DSP). This approach makes it possible to change adaptation algorithms in a flexible manner. Note that the predistortion itself must be done in real time, e.g., on an FPGA using fixed-point calculation.

For the adaptation of the predistorter, both an LMS algorithm [23] and an RLS solution [24] are used. The LMS algorithm is widely used due to its low complexity. The main limitation of the algorithm is the trade-off between its convergence speed and steady-state misadjustment, as both are governed by the step size. The step size dependency on the signal power is discussed in ([6], p. 643): the upper limit is inversely proportional to the signal power. That means that when halving the signal power, a doubling of the step size is required for unchanged performance. The speed of the convergence increases by using individually scaled adaptation step sizes for the different nonlinear orders of the signal (see [15] for a comparison between the scaled and nonscaled algorithms).

In this work, the conventional LMS approach used in linear systems is extended to memory polynomial predistorter adaptation. For this purpose, adaptation step sizes of all nonlinear orders are properly scaled. Thus we define

$$\mathbf{u}(n) = [u_1(n) \quad u_2(n) \quad \ldots \quad u_k(n) \quad \ldots \quad u_K(n)]^{\mathrm{T}} \quad (2)$$

where $u_k(n) = \hat{y}(\mathrm{n})|\hat{y}(n)|^{k-1}$ and $[\cdot]^T$ denotes matrix transpose. Then, to keep the step sizes within reasonable levels relative to $\mathbf{u}(n)$, they are normalized as follows:

$$\boldsymbol{\mu}_{\mathrm{LMS}} = \mu_{\mathrm{LMS}} \mathrm{diag}\left[\sigma_1^{-2} \, \ldots \, \sigma_k^{-2} \, \ldots \, \sigma_K^{-2}\right] \quad (3)$$

where

$$\sigma_k^2 = \frac{1}{N} \sum_{n=1}^{N} |u_k(n)|^2. \quad (4)$$

Thus, the modified LMS algorithm is given by

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \boldsymbol{\mu}_{\mathrm{LMS}} e^*(n) \mathbf{u}(n) \quad (5)$$

$$e(n) = z(n) - \mathbf{w}^{\mathrm{H}}(n) \mathbf{u}(n) \quad (6)$$

where $[\cdot]^H$ denotes Hermitian transpose. Note that if the signal powers are known in advance, these normalizations do not need to be carried out in the actual adaptation.

In addition to LMS, the RLS solution [24] is also used for the adaptation. In [25], the RLS solution is used for the memory polynomial predistortion. It is given by [25]

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \boldsymbol{\mu}_{\mathrm{RLS}}(n)\mathbf{u}(n)e^*(n) \tag{7}$$

$$\boldsymbol{\mu}_{\mathrm{RLS}}(n) = \lambda^{-1}\boldsymbol{\mu}_{\mathrm{RLS}}(n-1) - \frac{\lambda^{-2}\boldsymbol{\mu}_{\mathrm{RLS}}(n-1)\mathbf{u}^*(n)\mathbf{u}^{\mathrm{T}}(n)\boldsymbol{\mu}_{\mathrm{RLS}}(n-1)}{1+\lambda^{-1}\mathbf{u}^{\mathrm{T}}(n)\boldsymbol{\mu}_{\mathrm{RLS}}(n-1)\mathbf{u}^*(n)} \tag{8}$$

where λ is the forgetting factor and $\mathbf{u}(n)$ is defined in the same way as in (2).

As already discussed above, the adaptive algorithms can be implemented in a DSP, giving the possibility of changing the algorithm at any time. Implementations of both algorithms may be contained in the DSP, and in order to obtain both fast convergence and energy saving, the RLS solution could be used in the first iteration round and the LMS algorithm afterwards. To obtain benefits in practical implementations, the RLS may be dedicated to the calibration of the systems, and the LMS may be used during data transmission for tracking or fine tuning.

A long distance between the RAU and CU introduces one additional problem in the adaptive compensation of the RoF link: how to provide the feedback signal from the RAU to the CU. In practice, the feedback connection has to be arranged over another RoF link. Considering time-division duplexing (TDD) systems, the UL RoF link can be used as the feedback connection, see Fig. 1. In frequency-division duplexing (FDD) systems, a separate feedback connection may be needed. However, as the feedback connection is required only occasionally, due to slow changes of nonlinearity, another option could be to use the UL RoF link for feedback on request.

The feedback over the RoF link can be as nonlinear as the RoF link to be compensated, i.e., the DL RoF link in Fig. 1. Because the predistorter should ideally see only the nonlinearities it tries to compensate, the nonlinear, uncompensated feedback link would collapse the performance of the predistorter. A solution for that would be to use an approach where the UL RoF link is first compensated using a postdistorter and known training signal from the RAU, see Fig. 1. Then, the already compensated UL RoF link can be used as the feedback link for compensation of the DL RoF link. For more information on compensation studies in the presence of nonideal feedback, the reader is referred to [26].

IV. Results

A. Prototyping Environment

A block diagram of the prototype demonstration setup is shown in Fig. 5. The system consists of a host PC, an FPGA-based hardware platform and the RoF link itself. The PC, running Matlab, is used to control the measurements and provide an interface to the hardware. The hardware platform contains signal processing units on separate FPGA circuits in both the transmitter (TX) and receiver (RX) units. In order to verify the performance of the predistorter using fixed-point processing and to achieve the acceleration of real-time processing, an FPGA implementation of the predistorter was designed and integrated into one of the TX unit's XC2VP40 FPGAs [27].

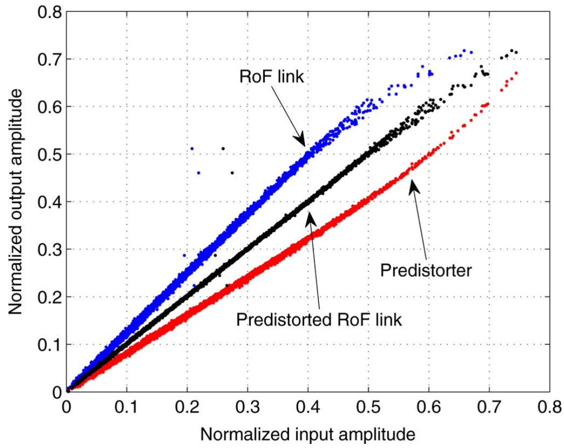


Fig. 6. Measured AM/AM of RoF link, predistorter, and predistorted RoF link.

At the transmitter side, the signal chain consists of conversion from complex in-phase and quadrature (IQ) signal components to a digital IF signal and digital-to-analog (D/A) conversion. The receiver unit, which is used to provide the feedback link, reverses these operations in the analog-to-digital (A/D) conversion and IF to IQ conversion (see the OFDM signal specifications in Section II). A vector signal analyzer at the RoF link output is used to monitor signal power levels and observe the signal's spectral behavior.

As depicted in Fig. 5, the signal can be predistorted either in software in the PC or in real time using fixed-point processing in the FPGA prior to being transmitted through the rest of the signal chain and RoF link. The predistorter in the FPGA operates on the baseband signal.

B. Measurements

In the measurements, the gain of the RoF link is scaled so that the maximum output signal amplitude is normalized to the maximum input signal amplitude, i.e., to unity. As discussed earlier, the predistorter memory length Q is set to 4 and nonlinearity order K to 5, having only odd orders in use. In the predistorter training, each iteration uses a signal block of 4000 samples and the predistorter is updated after each block.

First, to show the nonlinearity and memory of the RoF link, its amplitude-to-amplitude (AM/AM) and amplitude-to-phase (AM/PM) characteristics are plotted in Figs. 6 and 7 (obtained using the OFDM signal). In the same figures, the corresponding curves of the predistorter and predistorted RoF link are shown as well. Using predistortion, the nonlinearity is well compensated and the memory effects are considerably reduced.

As can be seen in Fig. 7, the RoF link induces some phase shift to the signal. When the average phase shift is compensated using, e.g., channel estimation, the residual noise-like effect on the signal constellation due to the nonlinearity is reduced, as shown in Fig. 8 (crosses). To show the performance improvement due to the compensation, the constellation of the compensated signal is also depicted in the same figure (circles). Here, a

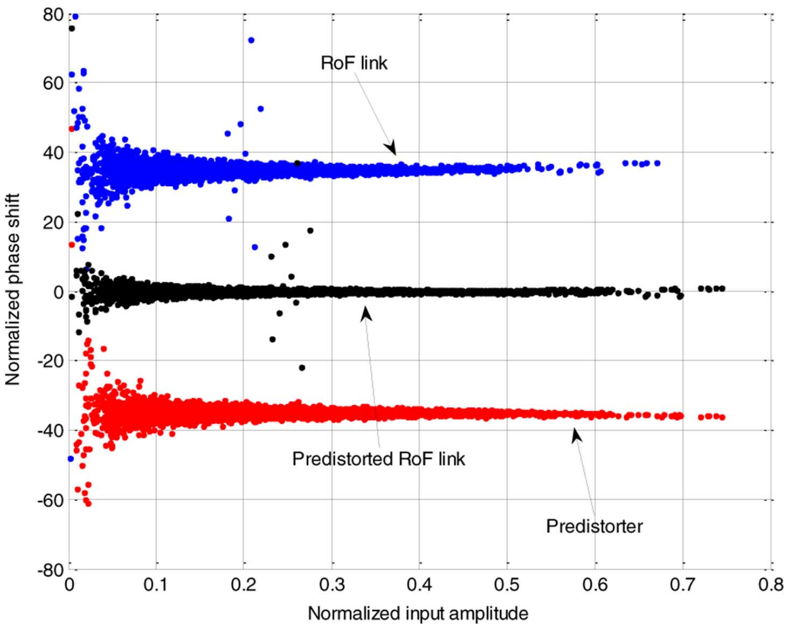


Fig. 7. Measured AM/PM of RoF link, predistorter, and predistorted RoF link.

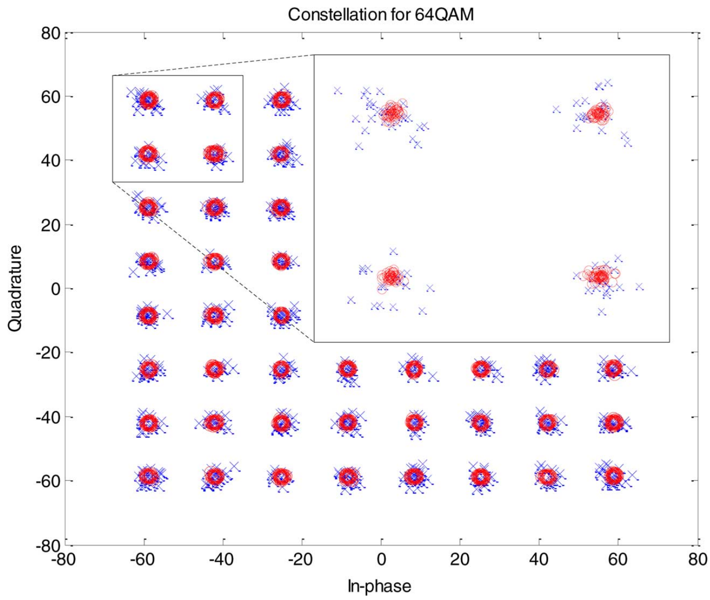


Fig. 8. Constellations of uncompensated (crosses) and predistorted (circles) signals.

signal power at the laser input of 8 dBm and the floating-point predistorter with the RLS solution for the adaptation are used.

Table I shows measured error vector magnitudes (EVMs) for the different predistorters (floating- and fixed-point) and adaptation algorithms, with different signal powers at the laser input. Using the floating-point predistorter with the RLS solution, the EVM can be reduced from 4.6% to 0.9% and from 3.6% to 0.7% when the signal powers are 8 dBm and 5 dBm, respectively. With the RLS+LMS combination (see Section III) and the LMS cases, the performance improvements are roughly similar. As can be seen, the fixed-point predistorter using a word length of 12 bits actually gives the same performance as the floating-point predistorter. With a word length of 10 bits, a small degradation is observed.

Using an 8-bit predistorter, it is clear that the accuracy and performance of the predistorter starts to deteriorate due to larger quantization errors. In addition, in this case, the performance with the RLS solution is worst. We assume that the inaccuracy

TABLE I
MEASURED EVMs

Algorithm	RLS	RLS+LMS	LMS	RLS	RLS+LMS	LMS
Signal power at laser input (dBm)		8			5	
Uncompensated EVM (%)		4.6			3.6	
Floating point PD EVM (%)	0.9	1.0	1.0	0.7	0.6	0.7
Fixed point PD (12 bit) EVM (%)	0.9	0.9	1.1	0.7	0.6	0.8
Fixed point PD (10 bit) EVM (%)	1.0	1.0	1.2	0.8	0.8	0.9
Fixed point PD (8 bit) EVM (%)	2.6	2.3	2.1	2.3	1.9	2.1

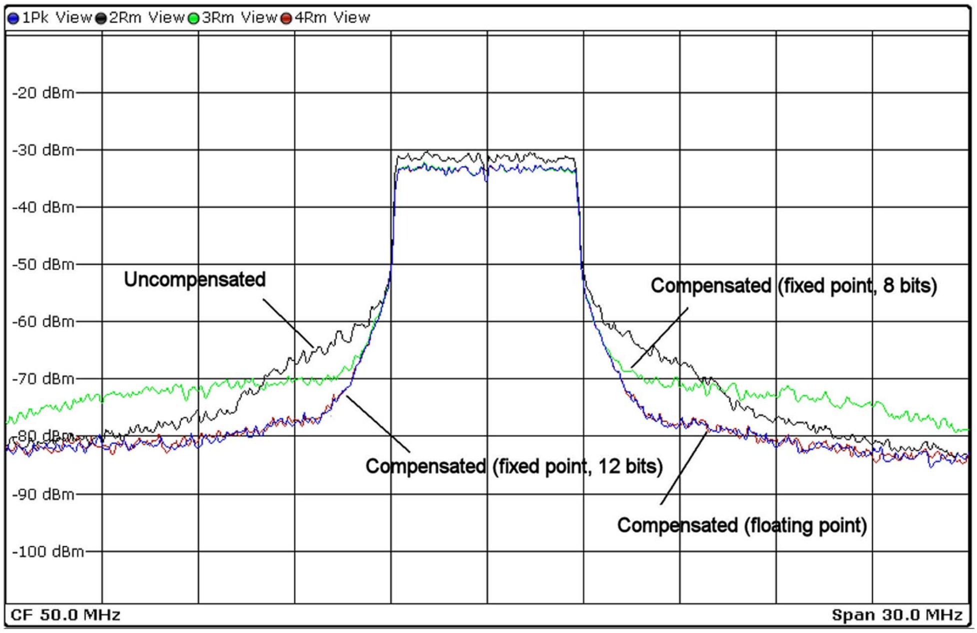


Fig. 9. Spectra of uncompensated, and compensated signals using floating-point, fixed-point (12 bits), and fixed-point (8 bits) predistorters.

due to the quantization errors accumulates in the various complex operations of the RLS solution, as stated in ([6], p. 659).

When using the RLS solution, convergence of the algorithm is achieved after just one iteration round, whereas the LMS algorithm takes about 30 iterations. The compensated EVM is calculated after the algorithms are converged. A ratio of average error power to average constellation power is used as a basis of the EVM calculations.

The step sizes for the LMS algorithm have been determined during several tests with the measurement platform and they give the maximum achievable speed of convergence. For the higher, i.e., 8-dBm, signal power at the laser input, the step size μ_{LMS} in (3) is set to 0.001, and for the lower signal power, to 0.0015. In the case of the RLS + LMS combination, the step sizes for the LMS are 0.0005. Here, the step size can be smaller because the algorithm is already converged due to the use of the RLS solution in the first iteration.

Finally, the signal spectra at the output of the uncompensated and compensated RoF link are shown in Fig. 9. Using the floating-point predistorter and the fixed-point predistorter with 12-bit word length as well, the spectrum sidelobes close to the signal band are about 10 dB lower than in the uncompensated case. The fixed-point predistorter having a word length of 8 bits does not give good performance, just as was found in the EVM tests.

As already mentioned, for the results shown in this paper, only odd-order terms in the predistorter have been used. Additional tests were carried out using the even-order terms as well in the predistorter (implemented in Matlab), but only slight performance improvements were observed. The EVM improvement varied by up to 0.3% only, and was dependent on the case. The reader is also referred to [22] where, using even- and odd-order terms, some performance improvements have been reported.

V. Conclusion

In this paper, we considered the adaptive compensation of a nonlinear RoF link. In particular, we presented an extension to the conventional LMS algorithm for memory-polynomial-based predistortion. In addition, we studied different combinations of the algorithms for the predistortion. To show the feasibility of our adaptive predistortion concept, we implemented the predistorter in hardware, built a real RoF link, and verified the performance by measurements. To the best of the authors' knowledge, this is the first time that the digital predistortion technique has been demonstrated for RoF links using an FPGA-based implementation and low-cost electro-optical link components.

The performance results demonstrate that distortion of the RoF link can be considerably diminished with a low-complexity design. Using the predistortion, the RoF link nonlinearity is well compensated and the memory effects are considerably reduced. Using the combination of the RLS and LMS algorithms, both fast convergence and low algorithmic complexity are achieved. The fixed-point predistorter with a word length of 12 bits gives performance as good as the floating-point predistorter.

In future work, RoF links operating at higher frequencies—as is often the case for real wireless systems—will be investigated. Operation at higher frequencies, nearer the laser relaxation resonance, can be expected to create greater dynamic nonlinearity (leading to higher-order memory effects) and will be more affected by fiber dispersion. In some cases, it may be necessary to use frequency conversion and transmission at an intermediate frequency on the RoF link, but in these cases the nonlinearities of the RF mixers would need to be considered.

REFERENCES

[1] *Radio Over Fiber Technologies for Mobile Communications Networks*, H. Al-Raweshidy and S. Komaki, Eds. Norwood, MA: Artech House, 2002.

[2] "Fibre optic networks for distributed, extendible heterogeneous radio architectures and service provisioning" [Online]. Available: http://www.ict-futon.eu/ FUTON project

[3] A. R. Shah and B. Jalali, "Adaptive equalisation for broadband predistortion linearisation of optical transmitters," *Proc. IEE—Optoelectron.*, vol. 152, pp. 16–32, Feb. 2005.

[4] X. N. Fernando and A. B. Sesay, "Adaptive asymmetric linearization of radio over fiber links for wireless access," *IEEE Trans. Veh. Technol.*, vol. 51, pp. 1576–1586, Nov. 2002.

[5] J. Kim, C. Park, J. Moon, and B. Kim, "Analysis of adaptive digital feedback linearization techniques," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 57, pp. 345–354, Feb. 2010.

[6] J. G. Proakis, *Digital Communications*. New York: McGraw-Hill, 1995.

[7] D. R. Morgan, Z. Ma, J. Kim, M. G. Zierdt, and J. Pastalan, "A generalized memory polynomial model for digital predistortion of RF power amplifier," *IEEE Trans. Signal Process.*, vol. 54, pp. 3852–3860, Oct. 2006.

[8] L. Tan and J. Jiang, "Adaptive Volterra filters for active control of nonlinear noise processes," *IEEE Trans. Signal Process.*, vol. 49, pp. 1667–1676, Aug. 2001.

[9] D. Chou and V. E. DeBrunner, "Novel adaptive nonlinear predistorters based on the direct learning algorithm," *IEEE Trans. Signal Process.*, vol. 55, pp. 120–133, Jan. 2007.

[10] W.-J. Kim, K.-J. Cho, S. P. Stapleton, and J.-H. Kim, "Piecewise pre-equalized linearization of the wireless transmitter with a Doherty amplifier," *IEEE Trans. Microw. Theory Tech.*, vol. 54, pp. 3469–3478, Sep. 2006.

[11] P. Celka, N. J. Bershad, and J.-M. Vesin, "Stochastic gradient identification of polynomial Wiener systems: Analysis and application," *IEEE Trans. Signal Process.*, vol. 49, pp. 301–309, Feb. 2001.

[12] H.-H. Chen, C.-H. Lin, P.-C. Huang, and J.-T. Chen, "Joint polynomial and look-up-table predistortion power amplifier linearization," *IEEE Trans. Circuits Syst. II Exp. Briefs.*, vol. 53, pp. 612–616, Aug. 2006.

[13] E. Aschbacher, M. Y. Cheong, P. Brunmayr, M. Rupp, and T. I. Laakso, "Prototype implementation of two efficient low-complexity digital predistortion algorithms," *EURASIP J. Adv. Signal Process.*, vol. 2008, p. 15, 2008, art. ID 473182.

[14] P. L. Gilabert, A. Cesari, G. Montoro, E. Bertran, and J.-M. Dilhac, "Multi-lookup table FPGA implementation of an adaptive digital predistorter for linearizing RF power amplifiers with memory effects," *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 2, pp. 372–384, Feb. 2008.

[15] A. Hekkala and M. Lasanen, "Performance of adaptive algorithms for compensation of radio over fiber links," in *Proc. IEEE Wireless Telecomm. Symp.*, Prague, Czech Republic, Apr. 2009, pp. 1–5.

[16] L. C. Vieira, N. J. Gomes, and A. Nkansah, "An experimental study on digital predistortion for radio-over-fiber links," in *Proc. SPIE-OSA-IEEE Asia Commun. Photon.*, Feb. 2011, vol. 7988, paper 798828.

[17] "D6.13.7 test scenarios and calibration cases issue 2," IST-4-027756, Dec. 2006, WINNER II, Tech. Rep..

[18] D. Wake, S. Pato, J. Pedro, E. Lopez, N. J. Gomes, and P. Monteiro, "A comparison of remote radio head optical transmission technologies for next generation wireless systems," in *Proc. IEEE Photon. Soc. Annu. Meet. (LEOS)*, Belek-Antalya, Turkey, Oct. 2009, pp. 442–443.

[19] C. H. Cox, III, *Analog Optical Links: Theory and Practice*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[20] L. C. Vieira, N. J. Gomes, A. Nkansah, and F. van Dijk, "Behavioral modeling of radio-over-fiber links using memory polynomials," in *Proc. IEEE Int. Top. Meet. Microw. Photon.*, Montreal, QC, Canada, Oct. 2010, pp. 85–88.

[21] L. Ding, G. T. Zhou, D. R. Morgan, Z. Ma, J. S. Kenney, J. Kim, and C. R. Giardina, "A robust digital baseband predistorter constructed using memory polynomials," *IEEE Trans. Commun.*, vol. 52, pp. 159–165, Jan. 2004.

[22] L. Ding and G. T. Zhou, "Effects of even-order nonlinear terms on power amplifier modeling and predistortion linearization," *IEEE Trans. Veh. Technol.*, vol. 53, pp. 156–162, Jan. 2004.

[23] B. Widrow and E. Walach, *Adaptive Inverse Control*. Upper Saddle River, NJ: Prentice-Hall, 1996.

[24] S. Haykin, *Adaptive Filter Theory*. Upper Saddle River, NJ: Prentice-Hall, 2002, ch. 9.

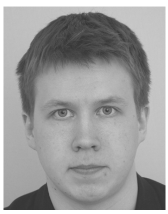
[25] R. Marsalek, "Contribution to the power amplifier linearization using digital baseband adaptive predistortion," Ph.D. dissertation, Inst. Gaspard Monge, Univ. de Marne la Vallee, Champs-sur-Marne, France, 2003.

[26] A. Hekkala, M. Lasanen, L. C. Vieira, N. J. Gomes, and A. Nkansah, "Architectures for joint compensation of RoF and PA with nonideal feedback," in *Proc. IEEE VTC Spring*, Taipei, Taiwan, May 2010, pp. 1–5.

[27] Virtex-II Pro and Virtex-II Pro X Platform FPGAs: Complete Data Sheet, Product Specification Xilinx, Inc., Nov. 5, 2007 [Online]. Available: http://www.xilinx.com/support/documentation/data_sheets/ds083.pdf

Atso Hekkala (M'09) received the M.Sc. degree in electrical engineering from the University of Oulu, Finland, in 2002. He is currently working toward the Ph.D. degree at the University of Oulu.

From 2002 to 2004 he was with the Centre for Wireless Communications at the University of Oulu. In 2004 he joined VTT Technical Research Centre of Finland, Oulu, as a Research Scientist. His current research interests include compensation of nonlinear transmitters in distributed antenna systems, adaptive signal processing, and cognitive radios.



Mikko Hiivala received the M.Sc. degree in information engineering from the University of Oulu, Finland, in 2010.

Since then he has worked for VTT Technical Research Centre of Finland, Oulu, as a Research Scientist. His current research topics include signal processing system implementation on FPGA and software portability enhancement for multicore platforms.

Mika Lasanen received the M.Sc. degree in electrical engineering from the University of Oulu, Finland, in 1998.

Since then he has worked for VTT Technical Research Centre of Finland, Oulu, as a Research Scientist and Project Manager. His current research topics are related to transmitter impairment compensation techniques and synchronization issues in distributed antenna systems.

Jari Perttu received the M.Sc. degree in information engineering from the Department of Electrical Engineering, University of Oulu, Finland, in 2006.

He has worked as a Research Scientist at VTT Technical Research Centre of Finland, Oulu, since 2007. He has been working with algorithm implementation and physical layer of OFDM systems for several years. His current research topics include FPGA implementation of DFE for OFDM-based wireless router systems.

Luis C. Vieira (GS'10) received the B.Eng. degree in electrical engineering from Universidade Federal de Santa Maria, Brazil, in 1992, the Postgraduate Diploma in telecommunications system engineering from Instituto Nacional de Telecomunicações, Brazil, in 1998, and the M.Sc. degree in electrical engineering and industrial informatics from Centro Federal de Educação Tecnológica do Paraná, Brazil, in 2003. He is currently working toward the Ph.D. degree in electronic engineering at the University of Kent, UK, on leave from Federal University of Technology—Paraná (UTFPR), Brazil, where he holds a lecturer position in Telecommunications. His present research interests include modeling and linearization of radio over fiber systems.

Nathan J. Gomes (M'92–SM'06) received the B.Sc. degree from the University of Sussex, U.K., in 1984 and the Ph.D. degree from University College London, U.K., in 1988, both in electronic engineering.

From 1988 to 1989 he held a Royal Society European Exchange Fellowship at ENST, Paris. Since late 1989, he has been at the University of Kent, U.K., where he is now a Reader in Broadband Communications. His present research interests include radio over fiber systems and networks, the photonic generation and transport of millimeter-wave signals, and photoreceivers for such applications.

Anthony Nkansah received the B.Eng. (with honors) degree in electronic engineering, the M.Sc. degree in broadband and mobile communication networks, and the Ph.D. degree in electronic engineering from the University of Kent, Canterbury, U.K., in 2000, 2001, and 2007, respectively.

His research interests include low-cost microwave and millimeter-wave radio-over-fiber networks and their deployment within premises.

PAPER V

Novel digital compensation approaches for envelope tracking amplifiers

Not available in the electronic version.

Series title and number
VTT Science 53

Title	**Compensation of transmitter nonlinearities using predistortion techniques** **Case studies of envelope tracking amplifiers and radio-over-fibre links**
Author(s)	Atso Hekkala
Abstract	This thesis studies compensation of nonlinear distortions introduced in the transmitters of wireless communication systems. In particular, adaptive predistortion of the envelope tracking (ET) amplifier and the radio-over-fibre (RoF) link is considered. The main goal is to develop compensation algorithms and architectures for predistortion. By providing a low attenuation and broadband solution, the RoF technology enables using cost-efficient and energy-efficient distributed antenna systems (DASs). Using highly efficient power amplifier (PA) structures, such as the ET amplifiers, energy efficiency of the transmitters is increased. Unfortunately, the RoF links and the ET amplifiers are inherently nonlinear. The results of this thesis indicate that these nonlinearities have to be taken into account when designing wireless communication systems. The nonlinearities can be compensated using the low complex adaptive predistortion techniques proposed in this thesis. In this thesis, a general architecture for the predistortion of the ET amplifier is proposed. Using the architecture, the performance of predistortion is demonstrated. In addition, new time misalignment compensation methods are studied. For the compensation of the RoF link, an extension to the conventional least mean square (LMS) algorithm for the memory polynomial-based predistortion is presented. In addition, different combinations of adaptive algorithms for predistortion are considered. From the compensation architecture point of view, the joint compensation of the RoF link and PA connected in series in the presence of nonlinear feedback is studied. Finally, feasibility of the adaptive predistortion concept is demonstrated by the measurements. The results presented in this thesis can be applied to any wireless communications systems. The performance studies demonstrate that distortions of the RoF link and the ET amplifier can be considerably diminished using a low-complexity design. To get even better results in terms of linearity and energy efficiency, the proposed predistortion techniques can be implemented together with other techniques, such as the peak-to-average power ratio (PAPR) reduction methods.
ISBN, ISSN	ISBN 978-951-38-8117-7 (Soft back ed.) ISBN 978-951-38-8118-4 (URL: http://www.vtt.fi/publications/index.jsp) ISSN-L 2242-119X ISSN 2242-119X (Print) ISSN 2242-1203 (Online)
Date	February 2014
Language	English, Finnish abstract
Pages	56 p. + app. 60 p.
Name of the project	
Commissioned by	
Keywords	Adaptive predistortion, compensation architecture, envelope tracking amplifier, LMS, power amplifier, radio-over-fibre, RLS
Publisher	VTT Technical Research Centre of Finland P.O. Box 1000, FI-02044 VTT, Finland, Tel. 020 722 111

Julkaisun sarja ja numero
VTT Science 53

Nimeke	**Lähettimen epälineaarisuuksien kompensointi esivääristystä käyttäen** **Esimerkkitapauksina verhokäyräseuraajavahvistin ja kuituoptinen radiolinkki**
Tekijä(t)	Atso Hekkala
Tiivistelmä	Tässä työssä tutkitaan lähettimen aiheuttamien epälineaaristen vääristymien kompensointia langattomissa tietoliikennejärjestelmissä. Erityisesti tarkastellaan verhokäyräseuraajavahvistimen (envelope tracking, ET) ja kuituoptisen radiolinkin (radio-over-fibre, RoF) adaptiivista esivääristystä. Päätavoitteena on kehittää esivääristysalgoritmeja ja -arkkitehtuureja. Laajakaistaisena ja vähän vaimentavana ratkaisuna RoF-teknologia mahdollistaa kustannus- ja energiatehokkaan hajautetun antennijärjestelmän (distributed antenna system, DAS) käytön. Lähettimen energiatehokkuutta voidaan lisätä käyttämällä suuren hyötysuhteen tehovahvistinarkkitehtuureja, kuten ET-vahvistimia. Valitettavasti RoF-linkit ja ET-vahvistimet ovat epälineaarisia. Tämän työn tulokset indikoivat, että langattomien tietoliikennejärjestelmien suunnittelussa nämä epälineaarisuudet täytyy ottaa huomioon. Epälineaarisuuksia voidaan kompensoida käyttämällä tässä työssä ehdotettuja yksinkertaisia adaptiivisia esivääristystekniikoita. Tässä työssä kuvataan ehdotus yleiseksi ET-vahvistimen esivääristysarkkitehtuuriksi. Esivääristyksen suorituskykyä demonstroidaan kyseistä arkkitehtuuria käyttäen. Lisäksi tutkitaan uusia tulosignaalien ajoitusvirheen kompensointimenetelmiä. Lisäksi tässä työssä esitetään tavanomaisen LMS-algoritmin laajennus muistipolynomiesivääristimelle. Työssä käsitellään myös erilaisia adaptiivisten algoritmien kombinaatioita RoF-linkin kompensointia varten. Sarjaan kytkettyjen RoF-linkin ja tehovahvistimen kompensointia tutkitaan tilanteessa, jossa myös takaisinkytkentä on epälineaarinen. Lopuksi adaptiivisen esivääristyksen konseptin toteutettavuus demonstroidaan mittauksilla. Tämän työn tuloksia voidaan soveltaa missä tahansa langattomassa tietoliikennejärjestelmässä. Suorituskykytarkastelut osoittavat, että RoF-linkin ja ET-vahvistimen aiheuttamia häiriöitä voidaan merkittävästi vähentää käyttäen yksinkertaisia kompensointimenetelmiä. Lineaarisuutta ja energiatehokkuutta voidaan parantaa implementoimalla tässä työssä ehdotettuja esivääristystekniikoita yhdessä muiden tekniikoiden, kuten huippu- ja keskiarvotehojen suhteen (peak-to-average power ratio, PAPR) pienentämisen, kanssa.
ISBN, ISSN	ISBN 978-951-38-8117-7 (nid.) ISBN 978-951-38-8118-4 (URL: http://www.vtt.fi/publications/index.jsp) ISSN-L 2242-119X ISSN 2242-119X (painettu) ISSN 2242-1203 (verkkojulkaisu)
Julkaisuaika	Helmikuu 2014
Kieli	Englanti, suomenkielinen tiivistelmä
Sivumäärä	56 s. + liitt. 60 s.
Projektin nimi	
Toimeksiantajat	
Avainsanat	Adaptiivinen esivääristys, kompensointiarkkitehtuuri, kuituoptinen radiolinkki, LMS, RLS, tehovahvistin, verhokäyräseuraajavahvistin
Julkaisija	VTT PL 1000, 02044 VTT, Puh. 020 722 111

VTT SCIENCE 53 Compensation of transmitter nonlinearities using predistortion ...

Compensation of transmitter nonlinearities using predistortion techniques

Case studies of envelope tracking amplifiers and radio-over-fibre links

This thesis studies compensation of nonlinear distortions introduced in the transmitters of wireless communication systems. In particular, adaptive predistortion of the envelope tracking (ET) amplifier and the radio-over-fibre (RoF) link is considered. By providing a low attenuation and broadband solution, the RoF technology enables using cost-efficient and energy-efficient distributed antenna systems. Using highly efficient power amplifier (PA) structures, such as the ET amplifiers, energy efficiency of the transmitters is increased. Unfortunately, the RoF links and the ET amplifiers are inherently nonlinear. The results of this thesis indicate that these nonlinearities have to be taken into account when designing wireless communication systems.

In this thesis, a general architecture for the predistortion of the ET amplifier is proposed. Using the architecture, the performance of predistortion is demonstrated. In addition, new time misalignment compensation methods are studied. For the compensation of the RoF link, an extension to the conventional LMS algorithm for the memory polynomial-based predistortion is presented. In addition, different combinations of adaptive algorithms for predistortion are considered. From the compensation architecture point of view, the joint compensation of the RoF link and PA connected in series in the presence of nonlinear feedback is studied. Finally, feasibility of the adaptive predistortion concept is demonstrated by the measurements.

The results presented in this thesis can be applied to any wireless communications systems. The performance studies demonstrate that distortions of the RoF link and the ET amplifier can be considerably diminished using a low-complexity design.

ISBN 978-951-38-8117-7 (Soft back ed.)
ISBN 978-951-38-8118-4 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN-L 2242-119X
ISSN 2242-119X (Print)
ISSN 2242-1203 (Online)