

Tijdschrift van het NERG

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DE VERENIGING NERG

Het NERG is een wetenschappelijke vereniging die zich ten doel stelt de kennis en het wetenschappelijk onderzoek op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie te bevorderen en de verbreiding en toepassing van die kennis te stimuleren.

BESTUUR

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vice-voorzitter
ir. E. Bottelier, secretaris
ir. J.G. van Hezewijk, penningmeester
ir. H.J. Visser, tijdschrift-manager
ir. B. Dunnebier,
programma-manager
ir. R.J. Kopmeiners, web-beheer
ir. F. Speelman,
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vacature, ledenwervings-manager

LIDMAATSCHAP

Voor het lidmaatschap wende men zich via het correspondentie-adres tot de secretaris of via de NERG website: <http://www.nerg.nl>. Het lidmaatschap van het NERG staat open voor hen, die aan een universiteit of hogeschool zijn afgestudeerd en die door hun kennis en ervaring bij kunnen dragen aan het NERG. De contributie wordt geheven per kalenderjaar en is inclusief abonnement op het Tijdschrift van het NERG en deelname aan vergaderingen, lezingen en excursies.

De jaarlijkse contributie bedraagt voor gewone leden € 43,- en voor studentleden € 21,50. Bij automatische incasso wordt € 2,- korting verleend. Gevorderde studenten aan een

universiteit of hogeschool komen in aanmerking voor het studentlidmaatschap. In bepaalde gevallen kunnen ook andere leden, na overleg met de penningmeester voor een gereduceerde contributie in aanmerking komen.

HET TIJDSCHRIFT

Het tijdschrift verschijnt vijf maal per jaar. Opgenomen worden artikelen op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie. Auteurs, die publicatie van hun onderzoek in het tijdschrift overwegen, wordt verzocht vroegtijdig contact op te nemen met de hoofdredacteur of een lid van de Tijdschriftcommissie.

Voor toestemming tot overnemen van (delen van) artikelen dient men zich te wenden tot de tijdschriftcommissie. Alle rechten berusten bij de auteur tenzij anders vermeld.

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Toekenning van de Vederprijs 2004 aan dr.ir. A. van Zelst

Allert van Zelst studeerde van 1994 tot 2000 aan de Technische Universiteit Eindhoven. Zijn afstudeeronderzoek verrichtte hij bij Bell Labs, Lucent Technologies, in Nieuwegein. Zijn opdracht was de ontwikkeling van algoritmes voor de verhoging van de datasnelheid van een draadloos "Local Area Network" (WLAN) door het toepassen van ruimteverdelingstechnieken (Space Division Multiplexing, SDM) met behulp van meervoudige antennes bij zender en ontvanger, ook wel aangeduid als "Multiple Input / Multiple Output" of MIMO technieken. Zijn werk op het toen nog zeer nieuwe onderzoeksgebied trok de aandacht: hij won de tweede prijs in de Europese IEEE Student Contest 2000 voor zijn paper "Space Division Multiplexing Algorithms".

Onder leiding van Prof. Brussaard zette hij zijn onderzoek op dit gebied voort als promotieonderzoek bij het "Wireless Systems Research Department" van Agere Systems. Daarbij werkte hij nauw samen met Bell Labs in Murray Hill, NJ (USA), waar hij ook enige tijd verbleef. Dit onderzoek maakte deel uit van het onderzoeksprogramma "B4

Radio@Hand" waarin Agere Systems, KPN Research/TNO Telecom, Philips Research en de leerstoel Radiocommunicatie van TU Eindhoven samenwerken aan de ontwikkeling van nieuwe draadloze systemen van de 3e en 4e generatie.

Voor snelle WLAN systemen was "Orthogonal Frequency Division Multiplexing" (OFDM) inmiddels algemeen aanvaard als de standaard voor data-overdracht, vanwege de robuustheid tegen de effecten van meerwegpropagatie. Allerts onderzoek betrof de combinatie van OFDM met MIMO technieken, waarvoor een zeer complex stelsel van algoritmes vereist is. Onder zijn leiding ontwikkelde Agere een z.g. "testbed" waarmee de snelheidswinst ook gedemonstreerd moest worden. Met dit testbed werd in 2003 een MIMO WLAN systeem gedemonstreerd met een datasnelheid van 162 Mbit/s, op dat moment het snelste netwerk van dit type ter wereld.

Na zijn promotie in april 2004 is Allert in dienst getreden bij Airgo Networks in Breukelen, één van de weinige "start-ups" in de wereld die op dit

Uitreiking van de Vederprijs 2004 aan dr.ir. A. van Zelst



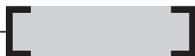
gebied tot succesvolle ontwikkeling van chips is gekomen. Hij werkt daar nauw samen met Dr.ir. R.D.J. van Nee, winnaar van de Vederprijs 2001.

De bijzondere uitdaging in dit project was om het gehele ontwerptraject te doorlopen van

- theoretische bestudering van de optimale combinatie van de twee complexe technieken OFDM en MIMO,
- het ontwikkelen van algoritmen voor de implementatie
- het implementeren van een "proof of concept"

Daarin gesteund door de onderzoeksgroep van Agere Systems heeft Allert deze uitdagende taak voortreffelijk volbracht. Niet alleen zijn proefschrift maar ook een indrukwekkende lijst van internationale publicaties (10 als eerste auteur) getuigen van het buitengewoon hoge niveau van zijn onderzoek.

Het bestuur van het Wetenschappelijk Radiofonds Veder was zeer onder de indruk van het hoge niveau van het werk, met name de combinatie van analytisch en experimenteel onderzoek, en heeft daarom in haar vergadering van 28 januari besloten de Vederprijs 2004 toe te kennen aan dr.ir. Allert van Zelst.



Van de redactie

Michel Arts

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Het is dus toch nog gelukt om dit jaar vier nummers van het tijdschrift uit te brengen. In dit laatste nummer van 2006 aandacht voor de uitreiking van de Vederprijs 2004 op 7 april 2005 aan dr.ir. A van Zelst. Tijdens de themabijeenkomst waar de Vederprijs werd uitgereikt hield Tim Schenk een presentatie over het gebruik van meerdere

draaggolven in draadloze communicatiesystemen. Het artikel dat hij naar aanleiding van deze presentatie schreef vindt U in dit nummer.

Tevens vindt U in dit nummer het verslag van de laatste algemene ledenvergadering die ook op 7 april gehouden werd.

Het laatste artikel van het jaar 2005 is van J.A.G. Akkermans. Dit artikel schreef hij naar aanleiding van zijn afstudeerwerk. Het gaat over het ontwerp van een rectenna (combinatie van antenne en gelijkrichter) voor de overdracht van energie.

Ten slotte wenst de redactie U de beste wensen voor 2006.



Aanwezigen conform getekende presentielijst:

Leden:

Arts, De Bruijn, Dijk, Dorgelo, Van Egmond, Van Hezewijk, Van Etten, Geels, Van Loon, Reynders, Schenk, Van der Schouw, Tasche, Visser.

Bestuur:

Baken, Regtien, Maartense, Bottelier, Dunnebier, Speelman.

Opening

10.20

Mededelingen

De voorzitter heet de aanwezigen welkom. Een aantal deelnemers zullen vertraagd of verhinderd zijn door problemen op het spoor.

Behandeling van notulen vorige algemene ledenvergadering

Pag 2

Naar aanleiding van punt van Van Egmond vraagt Baken aan Visser of het mogelijk is om iets te schrijven over overleden ereleden. Volgens Visser is het moeilijk omdat niemand meer iets over deze personen weet te schrijven. Van Egmond stelt voor om oudere leden aan te schrijven. Visser zal dit op zich nemen.

Pag 4

Baken zal veel van deze punten verder behandelen in een presentatie over de visie en missie.

Pag 7

Naar aanleiding van actiepunten: er zijn brieven van KNAW en URSI ontvangen. URSI wordt ondergebracht bij de KNAW.

Van Loon vraagt of er nog mensen zijn die nog onderwerpen hebben over "scanning the past". Hij vraagt ook over het redden van oude apparatuur, heeft niets van het bestuur hierover vernomen. Afbraak gaat volgens hem in rap tempo door. Dunnebier zegt dat het in ieder geval bekend moet zijn. TNO heeft in het verleden oude apparatuur met historische waarde overgenomen van een andere partij. Dunnebier vraagt om het in ieder geval aan het bestuur te melden als het gesignaleerd wordt. Van Loon heeft bijvoorbeeld bij Philips wat kunnen redden. Er is geen coördinatie volgens Van Loon. Baken vraagt hoe zoiets georganiseerd zal moeten worden. Speelman vraagt of de leden dit de taak van het NERG vinden. Hij ziet hier, helaas, geen mogelijkheid voor gezien alle andere taken van het bestuur. Instemming vanuit ALV. Volgens Tasche heeft het NERG niet de taak om apparatuur met historische waarde te redden (nostalgisch), maar meer

vanuit de wetenschappelijke overwegingen. Contact leggen met wetenschappelijke verzamelaars (bijv. eerste diode, etc.). Speelman concludeert dat het NERG kan faciliteren om contacten te leggen, misschien kan één van de (jongere) leden dit op zich nemen. Baken ziet daar een taak voor de overheid.

Actiepunten:

- Naam beheerder kelder Delft opzoeken.
- Suggesties naar het bestuur van Van Loon.
- Visser heeft lijst met geïnteresseerden, stuurt door naar Baken.

Behandeling jaarverslag 2004

Verantwoording bestuur

Het hoofdprobleem afgelopen jaar was om het bestuur op sterkte te krijgen. De tijdschriftencommissie krijgt een nieuwe voorzitter. Een nieuwe penningmeester treedt aan. Going concern (de dagelijkse gang van zaken) zijn themabijeenkomsten en het tijdschrift. Het bestuur is verder gegaan met het definiëren en uitdragen van een visie. In deze ALV wordt een presentatie van het Visie en Missie document gedaan.

Van Egmond: de achterkant van het tijdschrift heeft sponsors die nu niet meer bestaan.

Visser: de kaften worden eens per jaar bijgewerkt. Zodra de huidige voorraad op is, wordt een nieuwe kافت gemaakt waar sponsoren niet meer opstaan.

Themabijeenkomsten

Vorig jaar werd gepland het aantal terug te schroeven en de kwaliteit te verhogen. Toch is er een groot aantal themabijeenkomsten geweest van hoge kwaliteit, die ook goed werden bezocht. Er is vruchtbaar samengewerkt met het KiVi. Betreffend de vraag waarom leden wel of niet komen → velen hebben problemen themabijeenkomsten te combineren met het werk. Oplossing zou zijn de themabijeenkomsten naar de avond te verschuiven en te regionaliseren. Een aantal van 50-80 deelnemers is streven. De themabijeenkomst "EM-velden en maatschappij" trok 100 deelnemers en werd hoog gewaardeerd.

Themabijeenkomsten op locatie (Philips, ESA) drukken de kosten voor het NERG.

Tijdschrift

De kopij komt in voldoende mate binnen. Het probleem is een gebrek aan mankracht. In praktijk komt het werk op 2 man neer. Redigeren kost heel veel werk, hierbij worden indien nodig ook bestuursleden belast. Het idee nu is een vaste kernredactie te maken, aangevuld met freelancers.

Van Egmond meldt zich aan als vrijwilliger.

Redigeren is overigens steeds taak van de hoofdredacteur. De taak van de tijdschriftmanager blijft het zorgen voor voldoende input / kopij.

Website

Het idee is artikelen op de site te ontsluiten. Logistiek is dit lastiger, kost het meer tijd en menskracht, die er nu juist niet is.

Onderwijscommissie

Gecommitteerden zijn actief bij onderwijsinstellingen. Rens & Rens is 2 keer failliet gegaan en doorgestart. NERG is van mening dat schuld van Rens & Rens aan NERG eerst afbetaald moet worden. Dit zal beleid zijn. Een dreigende schuld is niet gerealiseerd: NERG heeft dit tegengehouden (zie onder). Rens & Rens wordt intussen door eigenaren beschouwd als bedrijf (en impliciet daarmee de leerlingen). Dit is op zich een kwalijke ontwikkeling en gaat ten koste van het eigenlijke doel: de leerlingen en hun diploma. De HBO-erkenning is er nog (net).

PT-opleidingen is niet van start gegaan. Er wordt gezocht naar alternatieve cursussen en markt-onderzoek uitgevoerd.

Contactcommissie

Nederlands URSI-committee (NUC): Recent is er een brief ontvangen van Van Ardenne (NUC) en KNAW. KNAW heeft zich positief bereid verklaard NUC te begeleiden. De overdracht van NUC van NERG naar KNAW gaat aanvangen (financieel en administratief). Overigens zal dit het gezamenlijk organiseren van themabijeenkomsten niet in de weg staan.

Externe relaties:

ITU: op 12 april 2005 is er een gesprek met EZ betreffend een youth contest. De winnaar daarvan gaat naar een internationaal forum. Van Egmond verzoekt NERG hierbij aangesloten te blijven.

Baken suggereert dit gesprek aan te grijpen om over samenwerking te discussiëren.

Er is ook gesproken over samenwerking met de student branches van IEEE. Dit heeft niet tot een vervolg geleid.

Vroeger waren student branches erg actief. Studenten lijkt tegenwoordig minder tijd te hebben voor dit soort activiteiten. NERG kan wellicht daarin springen. Baken en Regtien nemen actie (spreken met ETV Delft en Scintilla Enschede). Is er samen iets te organiseren? Wellicht in combinatie met studenten verenigingen ODIN (TUE), ETV (TUD) en NERG, waarbij NERG faciliteert.

Dorgelo vraagt hoe de studentenvereniging hierin passen. NERG bestuur neemt dit mee. Een heldere visie hierop volgt.

Van Etten en Noordanus zitten in IEEE Benelux. Dorgelo suggereert dat Baken contact met Van Etten opneemt.

Financiële verslagen

In het algemeen zijn er meevalende resultaten door minder aantal tijdschriften (hoewel rekening laatste nummer nog ontbreekt) alsook themabijeenkomsten op locatie. We zijn daarmee ruimschoots in de plus geëindigd.

Er wordt gevraagd waarom opbrengsten tegoeden lager zijn als begroot. Dit is een fout in begroting. Het betreft met name zeer waardevaste papieren. De gelden t.b.v. reservefondsen URSI en FBAC zijn hierin niet meegerekend, wat dit kan verklaren. Deze opmerking staat overigens wel in het verslag ("rente wordt naar rato toegerekend naar ..") Kosten van themabijeenkomsten omvatten ook

convocaten, zaalhuur, borrel, presentje spreker, ...

Verslag kascommissie

Tasche leest verklaring van de kascommissie voor. Tasche en Van Egmond hebben boekhouding gecontroleerd en in orde bevonden. Kascommissie adviseert decharge te verlenen, hetgeen geschiedt.

Ballotagecommissie

Er heeft geen ballotage plaatsgevonden.

Decharge bestuur voor gevoerde beleid

De ALV verleend decharge.

Overige correcties

- a. pagina II: Inhoudsopgave - paragraaf 3.3 (ITU) mist, paragraaf 3.3 (ISSLS) zou paragraafnummer 3.4 moeten hebben.
- b. Pagina 1: Samenstelling Programmacommissie NERG - Titulatuur B. Dunnebier incorrect, dit moet ir. B. Dunnebier PDEng zijn.
- c. Pagina 1: Samenstelling Kascommissie 2004 - Voorletters van Van Egmond incorrect: dit moet J. van Egmond zijn.
- d. Pagina 13: Exploitatierkening 2004 - Het format van de post nadelig saldo moet positief zijn. (Blijft overigens wel een negatief bedrag voor NERG.)

Behandeling Jaarplan 2005

Missie / visie

Baken presenteert de maatschappelijke ontwikkelingen: Hij schetst maatschappelijke ontwikkelingen: het vastlopen van de maatschappij in de huidige ICT (of eigenlijk het gebrek daaraan).

Wat mist is het regisseren van de ICT over de sectoren heen.

Speelman presenteert de visie en het beleid van NERG de komende jaren: De consequenties voor het NERG: het Going concern - het NERG bedrijf draaiende houden en de Visie en missie - waarheen willen we, gelet op beschikbare capaciteiten?

Reacties uit de zaal:

- Heeft NERG het apparaat om dit te realiseren: medewerkers, leden?
→ Het bestuur kan dit niet alleen. De leden wordt nadrukkelijk om ondersteuning gevraagd (geen free lunch).
- Vroeger werden pas afgestudeerden benaderd. Dit loopt op dit moment niet, m.u.v. Rens & Rens (lidmaatschap gereduceerd tarief)
→ De pas afgestudeerden lijken te druk met andere zaken. De vraag is (of duidelijk is) wat NERG een pas afgestudeerde als toegevoegde waarde kan bieden.
- Er waren altijd themabijeenkomsten op universiteiten. De leerstoelen kregen gelegenheid hun beste student af te vaardigen.
→ Het is moeilijk daar voet aan de grond te krijgen. NERG pakt dit op. Dit gecombineerd worden met de paper contest van de student branches. (Voorselectie papers in themabijeenkomst, ..)
- Betrekken BV Nederland: kunnen er partners gevonden worden? Kan de wetenschappelijke pers benaderd worden?
→ NERG heeft daar wat stapjes gemaakt. Voorbeeld de themabijeenkomst EM-velden

en maatschappij. Hier lijkt follow-up uit te komen. De pech is dat NERG hier op dit moment niet in de gelegenheid is zelf leidend in te zijn.

Begroting 2005

Themabijeenkomsten: de bepalende kosten zijn hier de convocaten. Gezien het aantal bijeenkomsten op locatie, zijn de kosten daarvan minder. Met name het aantal organiserende leden is hier erg beperkend. Er wordt een dringend beroep gedaan op de leden, eventueel free-lance, mee te helpen.

Onderwijs: Dorgelo en Speelman denken na over onderwijsbeleid.

Externe relaties - ISSLS: Speelman beheert dit nu, maar ziet graag een opvolger, gezien zijn werkgebied niet meer aansluit op dit moment.

Tijdschrift: NERG staat een geleidelijke overgang naar een digitaal tijdschrift (met fysiek jaarboek aan het eind van het jaar) voor. Het bestuur gaat hier zorgvuldig mee om, en houdt in het achterhoofd dat de convocaten en het tijdschrift op dit moment het enige fysieke contact vormt met de leden.

Financieel: de activiteiten zullen bepalen of er een negatief saldo ontstaat (het tijdschrift en de themabijeenkomsten zullen hier met name bepalend in zijn). De reserves staan dat op dit moment (nog) wel toe.

Er wordt de ALV gevraagd of het mandaat om de contributie te verhogen met maximaal 5 euro gehandhaafd mag blijven (besluit uit 2004). De ALV gaat akkoord.

Verkiezingen: de ALV gaat akkoord met alle voorgenomen benoemingen. De heer van Hezewijk (penningmeester) stelt zich voor. De voorzitter bedankt Peter Maartense (ex-penningmeester) voor zijn inzet.

Kascommissie: het nieuw lid is de heer Geels.

De ballotagecommissie: statutair moet deze commissie bestaan.

Voorstel NERG: is het zinvol deze leden te ontslaan, en 3 leden uit het bestuur te benoemen? De voormalig leden kunnen eventueel een actieve rol vervullen. Het bestuur zoekt uit of de statuten dit toestaan en vraagt de mening aan de leden der ballotagecommissie. Een besluit wordt voorzien in 2006. De ballotagecommissie is er juist om allerlei lieden die om commerciële reden het lidmaatschap van NERG gebruiken of alleen om op CV's te pronken te weren.

Rondvraag

- a. De heer Dijk: de vermelding van donateurs op achterzijde tijdschrift gaat gewijzigd worden zodra de voorraad op is. (Vermelding van de sponsoren dan in het tijdschrift).
- b. Er wordt een lijst met afkortingen opgenomen in het jaarverslag en jaarplan.

Sluiting door de voorzitter om 12.36

Actiepuntenlijst

- | | |
|---------|---|
| 0506-01 | Bottelier
Redactionele aanpassingen jaarverslag 2005. |
| 0506-02 | Visser
Benader oudere leden om tekst aan te leveren over overleden leden. |
| 0506-3 | Alle leden, Van Loon
Suggesties m.b.t. oude apparatuur met wetenschappelijk waarde door geven aan bestuur. |
| 0506-4 | Baken
Overleg met Van Etten over relatie met IEEE. |

Afkortingen:

- | | |
|-------|---|
| ALV: | Algemene Leden Vergadering. |
| KNAW: | Koninklijke Nederlandse Akademie van Wetenschappen. |
| URSI: | International Union of Radio Science (Union Radio-Scientifique Internationale). |
| NUC: | Nederlands URSI-committee. |

ODIN: Communicatiedispuut ODIN is een dispuut van de elektrotechnische studenten vereniging Thor aan de Faculteit Elektrotechniek van de Technische Universiteit Eindhoven. Zij richt zich op de telecommunicatie en de informatietechnologie.

ETV: Elektrotechnische Vereniging voor studenten elektrotechniek aan de Technische Universiteit Delft.

IEEE: Institute of Electrical and Electronics Engineers.

FBAC: Fonds Bijzondere Activiteiten, een fonds waarin het (grote) netto resultaat van NERG activiteiten in een ver verleden is gestort.



Multiple Carriers in Wireless Communications – Curse or Blessing?

Tim C.W. Schenk, Peter F.M. Smulders
and Erik R. Fledderus

Abstract

The use of multi-carrier techniques is a natural choice when regarding wireless systems with high bandwidths and for which the application environment exhibits severe multipath propagation. These techniques provide a way to cope with and benefit from the time-dispersive channel. This, however, comes at the cost of a higher sensitivity to imperfections in the analogue radio frequency front-end. This paper illustrates the sensitivity of the most frequently used multi-carrier technique, i.e. orthogonal frequency division multiplexing (OFDM), to three of the main impairments: phase noise, IQ imbalance and nonlinearities. Furthermore, it is shown that the use of digital signal processing can largely compensate the effects of these non-idealities, overcoming the disadvantages of the use of multi-carrier techniques.

Index Terms — Wideband communication, multipath propagation, physical layer, orthogonal frequency division multiplexing (OFDM), radio front-end impairments, digital compensation.

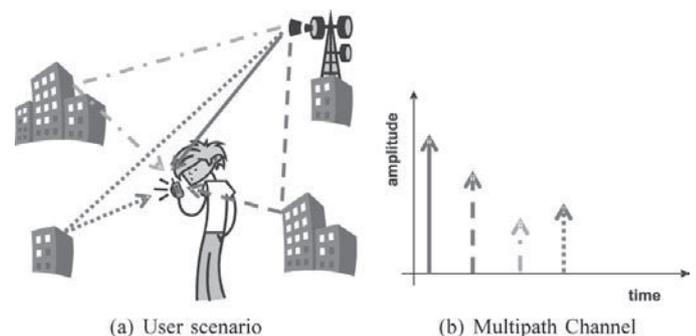
1. Introduction

The application of digital modulation is well established to convey data between the transmitter (TX) and receiver (RX) of a wireless communication system. It enables the use of advanced signal processing and coding techniques to improve the transmission quality. Where the application area of these kinds of systems was traditionally in point-to-point links (e.g. in satellite communications and microwave radio links), it has moved over the last decades towards terrestrial wireless, mobile and indoor networks. In parallel, the ever increasing demand for higher speeds in these kinds of networks, has caused a move from narrowband towards wideband systems.

Wireless networks are currently deployed in urban areas and in indoor environments, like offices and homes. An example for the former are GPRS and UMTS and for the latter wireless LAN (Wi-Fi) and Bluetooth. In these environments the transmitted signal experiences multipath propagation before reaching the RX. This means that multiple copies of the transmitted signal arrive with different delays and attenuations at the RX, see Fig. 1. The effect is that the response of the wireless channel is frequency selective and that delayed versions of the transmitted symbols leak into neighbouring symbols, causing inter-symbol interference (ISI). The influence of the multipath on the system performance is generally low, when the largest channel delay is small compared to the symbol time of the system. Or when, similarly, the system bandwidth is small compared to the coherence bandwidth. For those cases the influence of the channel can generally be easily removed using an equalizer with a few taps or a rake receiver with several fingers.

As the bandwidth, however, increases and systems move towards more time-dispersive environments (e.g. offices), these solutions become highly complex. Hereto, the use of *multiple carriers* was pro-

Fig. 1. Wireless communication in a multipath environment.



posed. In these techniques the whole system bandwidth is subdivided into several parallel narrow subbands. When this is implemented in the analogue domain it requires multiple carriers for frequency conversion and steep bandpass filters to separate the non-overlapping subchannels. Therefore, efficient implementations in the digital domain were proposed. The most applied version of these techniques is based on the digital Fourier transform (DFT) and named orthogonal frequency division multiplexing (OFDM), the basics of which will be treated in Section II.

Although OFDM exhibits a high spectral efficiency and the ability to use the multipath channel to its advantage, it has several disadvantages when compared with traditional single carrier systems. These disadvantages lie mainly in the constraints it puts on the quality of the analogue radio frequency (RF) front-end of both TX and RX. The influence of the most important imperfections on the system performance are treated in Section III-A, Section IV-A and Section V-A.

Since stringent specifications for the front-end of the regarded wireless system are required, the analogue part is the most expensive part of the system. Furthermore, Moore's law will influence the digital part in terms of size and price, but has little impact on the analogue part, i.e. the RF front-end; therefore, this part will dominate over time the performance and price of the radio system. Therefore, this paper also addresses digital signal processing based algorithms in the baseband part of the system, which are designed to suppress the influence of the analogue impairments. Examples hereof are presented in Section III-B, Section IV-B and Section V-B. A design incorporating these digital compensation techniques allows for higher impairment levels, and thus opens the door for cheaper and more optimized implementation of the RF front-end, e.g., the use of RF CMOS or homodyne transmitters/receivers. This of course at the cost of higher complexity in the digital part.

II. Orthogonal Frequency Division Multiplexing (OFDM)

For a comprehensive description of OFDM and its application in different wireless systems, the reader is referred to [1], [2] and [3]. Here we will treat the basic concept of OFDM and illustrate the application of the technique for three wireless systems.

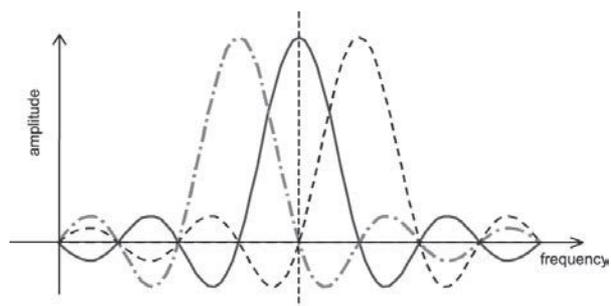
A. OFDM basics

The concept of using the discrete Fourier transform (DFT) as part of the digital modulation/demodulation in TX and RX part of the wireless system to achieve parallel data transmission was proposed in the early seventies by Weinstein and Ebert in their seminal paper [4]. Due to the properties of the DFT the subchannels are shaped like $\sin(x)/x$. An example of spectrum of three OFDM subcarriers is shown in Fig. 2, which shows that spectra are partly overlapping, significantly increasing the spectral efficiency as compared to conventional non-overlapping multi-carrier systems. It is clear, however, from Fig. 2 that the separation of the different carriers can not be carried out by bandpass filtering. Therefore, baseband processing is applied which exploits the *orthogonality* property of the subcarriers. This property is apparent from Fig. 2, where at the the maximum of one subcarrier all other carriers have a zero amplitude.

The same OFDM signal is depicted in the time-domain in Fig. 3. From this figure it can be concluded that the symbol length contains $\{1, 2, 3\}$ periods of the signal on the different carriers, respectively. Here the number of periods depends on the position of the subcarrier within the OFDM spectrum. To increase the robustness of the OFDM system against ISI, caused by multipath propagation, the addition of a cyclic extension of the symbols was proposed in [4]. Hereto the symbol length is prolonged for N_g samples with a guard interval (GI), which basically prefixes a copy of the last N_g samples to the start of the OFDM symbol. If N_g is chosen sufficiently large compared to the channel length, the ISI is contained in the GI of the symbol. Since it is redundant information it can be disregarded at the RX, removing the influence of ISI.

Since the addition of a GI decreases the effective datarate of the system, the ratio between the number of carriers N_c , which is equal to the symbol

Fig. 2. Spectra of three subcarrier forming an OFDM signal.



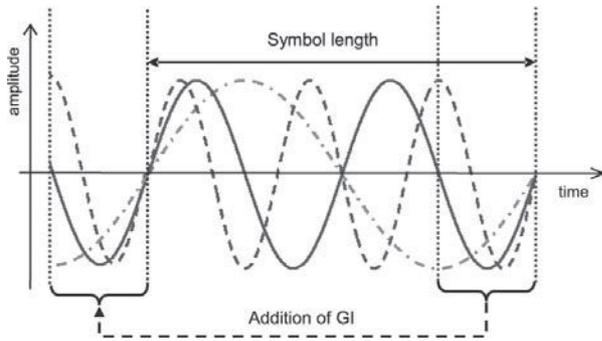


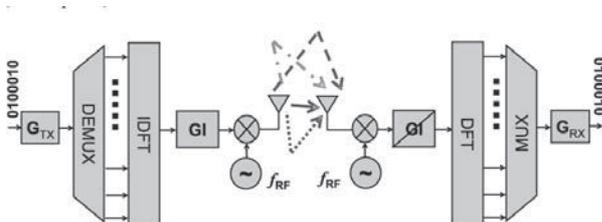
Fig. 3. OFDM signal in the time-domain, showing the addition of the guard interval (GI).

length in samples, and the GI length N_g is an important design parameter. It must be chosen in a tradeoff between ISI robustness and effective data-rate.

The basic OFDM processing in both TX and RX is summarized in the block diagram of Fig. 4. First the baseband processing to the input bitstream is applied, e.g., interleaving, channel coding, puncturing and mapping to complex symbols, here modelled by the block G_{TX} . The complex signal is then, after being demultiplexed (DEMUX), fed to the inverse DFT, which converts the signal to the time domain. Many efficient implementations of the (I)DFT exist, which overcome the previously regarded insurmountable complexity of this operation. Subsequently, a GI is added to the signal. Then the signal is converted to the analogue domain and up converted to RF f_{RF} . Then the signal is transmitted through the wireless (multipath) channel.

The received signal is, subsequently, downconverted to baseband by the RF RX front-end. The output of the analogue-to-digital converter is then passed to the RX baseband processing. This processing removes the GI, which annuls the influence of the ISI. The DFT processing then separates the signals on the different carriers. The multiplexed (MUX) data stream is then processed in the RX processing, here depicted as block G_{RX} , where, e.g.,

Fig. 4. OFDM system block diagram, showing a generic model for the transmitter and receiver.



channel equalization, decoding and deinterleaving are performed.

B. Turning multipath into an advantage

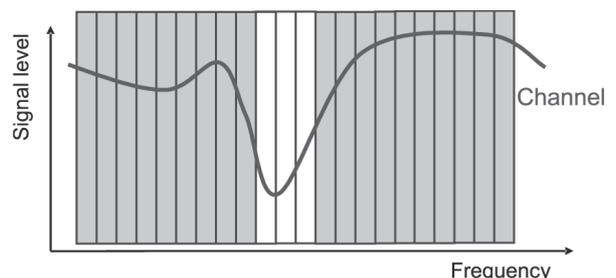
As mentioned above, the influence of the ISI caused by multipath propagation is removed at the receiver, when the GI is chosen long enough. The other effect of the multipath, the frequency selective fading, remains. Now, however, since the bandwidth is subdivided into parallel carriers, the subcarrier bandwidth is smaller than the channel coherence bandwidth. That is why the channel can be regarded as frequency flat for a certain carrier. This enables to use of a single tap equalizer per subcarrier to compensate for the channel influence.

If we assume the noise experienced in the system is white, the subcarriers having a lower channel transfer experience a lower signal-to-noise ratio (SNR). The detection of the transmitted symbols on such subcarriers yields a higher probability of error. This is schematically depicted in Fig. 5. Here the white carriers have a low probability of correct detection of the transmitted symbols.

1) Channel coding:

The performance of OFDM in frequency selective fading can be largely improved by the use of channel coding, yielding *coded* OFDM (COFDM). Here the bits are encoded in codewords, which are spread over the different subcarriers using an interleaver. Since the codewords are spread over the different carriers, the probability that a whole codeword is received on a channel with low transfer is lower and thus, the resulting probability of error detection is also lower. It can be shown that the performance of a COFDM system will improve with increasing frequency selectivity, up to channel lengths where ISI occurs. In this way the system benefits from the multipath channel.

Fig. 5. Subcarriers of an OFDM system experiencing a frequency selective channel.



2) Adaptive modulation:

Another way to cope with the multipath is the use of *adaptive modulation*. In this approach an estimate of the channel is available at the TX side of the wireless link. This can be obtained by either using the reciprocity of the channel or by the use of a feedback channel. This channel estimate, as mentioned above, relates to the SNR experienced at the RX. In adaptive modulation, now, subchannels with high channel transfers, or equivalently high SNRs, are assigned symbols of higher order modulation and subchannels with low channel transfer are assigned symbols from a lower order modulation or even no symbols. This is based on the fact that high order multi-level modulations, e.g., M -QAM and M -PSK modulations with high M , achieve a high bit rate per subcarriers, but also require a high SNR for reliable detection. In conventional OFDM, in contrast, all subchannels carry symbols from the same modulation size. Here the subchannels with the lowest SNR determine the probability of error and thus the modulation format. In contrast, a system based on adaptive modulation can maximize the total throughput for a certain probability of error.

The use of adaptive modulation is illustrated in Fig. 6. Here two subcarriers with a very low channel transfer are assigned no bits, nine subcarriers with moderate channel transfer carry 1 bit/subcarrier (e.g., by the use of BPSK modulation) and the eleven subcarriers with the highest channel transfer are assigned 2 bits/subcarrier (e.g., by the use of QPSK modulation). In the case of conventional OFDM all carrier would have been assigned 1 bit/subcarrier, clearly showing the gain of adaptive modulation.

Fig. 6. Adaptive modulation.

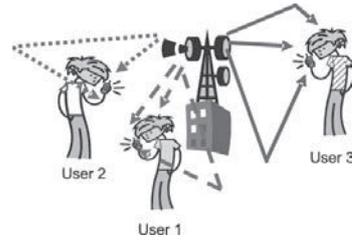
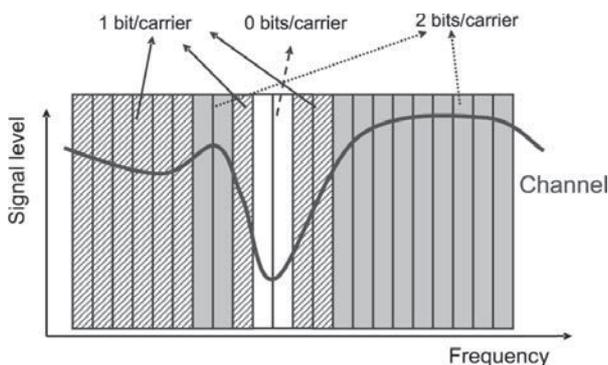


Fig. 7. User scenario for a system applying OFDMA.

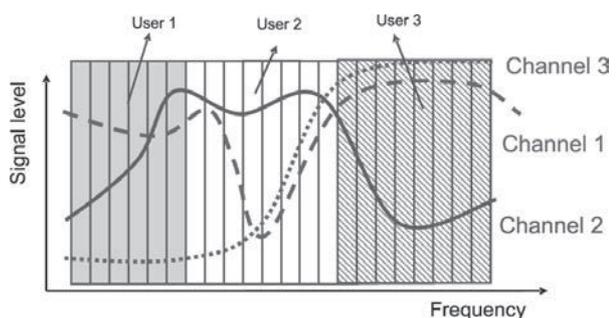
3) Orthogonal frequency division multiple access:

The multi-carrier technique OFDM can also be used as a multiple access technique: *Orthogonal frequency division multiple access* (OFDMA). In contrast to conventional OFDM, where all carriers are assigned to one user, in OFDMA the carriers are subdivided between the different users. The scenario of such a scheme is depicted in Fig. 7, where multiple users are receiving simultaneously.

Since all the users have their own location, the signals transmitted/received by the users experience different multipath channels. Therefore, also the frequency response of channels corresponding to the different users will differ. In OFDMA we can exploit this to our advantage by assigning those subcarriers to an user, where its channel transfer is high. Clearly this, as for adaptive modulation, requires some knowledge about the channel transfer.

The use of OFDMA is illustrated in Fig. 8, where the left block of carriers is assigned to user 1, the middle to user 2 and the right block to user 3. It is noted that although also channel 1 has its maximum transfer in the right block of subcarriers, it is assigned to user 3, since channel 3 has a low transfer in the left block, where the transfer of channel 1 is still acceptable. Although the assignment is applied in blocks of carriers here, other patterns might be more optimal, especially

Fig. 8. OFDMA: a multiple access scheme based on OFDM.



when this multiple-access technique is combined with channel-coding. For instance individual carriers throughout the spectrum can be assigned to a user, resulting into an interleaved carrier pattern for the different users.

The advantage of OFDMA is that multiple users can be receive/transmit simultaneously, and that the channel transfer is optimized for the combination of users.

C. Wireless Systems using OFDM

The application of OFDM is currently standardized for use in many different kinds of wireless systems, including wireless personal-area-network (PAN), local-area-network (LAN) and metropolitan-area-network (MAN), digital audio broadcasting and digital video broadcasting. To illustrate the application of OFDM in these kinds of systems, the system parameters of Wireless LAN, Ultra Wideband and Wireless MAN are treated here.

1) Wireless LAN:

The application of OFDM for wireless local-area-networks (WLANs) was first standardized in 1999 as IEEE 802.11a [5], often referred to as Wi-Fi, where it was applied to the 5 GHz frequency band. A similar system was standardized within ETSI under the name of HiperLAN/2. Both systems specify a system with 20 MHz bandwidth, 64 subcarriers and a GI-length of 16 samples (800 ns). A subset of 48 carriers is used for data transmission, 4 are used for synchronization purposes and the remaining carriers (at the sides of the band) are used as guard bands to minimize the out-of-band radiation. The system applies BPSK, QPSK, 16QAM and 64-QAM modulation, convolutional coding with rates varying from 1/2 to 3/4, creating data rates ranging from 6 Mbps up to 54 Mbps.

To enable higher speeds in the 2.4 GHz ISM band, where up to then the IEEE 802.11b standard was deployed, the design of the IEEE 802.11a OFDM physical layer (PHY) was ported to the 2.4 GHz band in 2003. This was standardized in the IEEE 802.11g standard [6], which combines the OFDM PHY with the IEEE 802.11b PHY.

2) Ultra Wideband:

Recently, the application of OFDM has been proposed for ultra wideband (UWB) communications [7] under the IEEE 802.15.3a PAN framework. This

proposal applies a signal bandwidth of 528 MHz, which is divided into 128 subcarriers of which 100 are used for data transmission. The system is based on what is called multiband OFDM, where consecutive symbols are transmitted in different frequency bands. Initial deployment is foreseen in the 3.1-4.9 GHz band, but extensions towards bands up to 10 GHz are envisioned for the future. The proposal is based on QPSK modulation and a variable coding rate resulting into a data rate varying from 53.3 Mbps up to 480 Mbps. Since the allowed transmit powers for these types of systems are low, the application is foreseen in systems combining low cell radii and high data rates.

In parallel to the standardisation by the IEEE, a similar proposal was accepted in May 2005 as the wireless USB [8] specification. Different vendors are now starting to deliver products based on this specification.

3) Wireless MAN:

The use of OFDM has also been standardized for application in outdoor networks, for example under the IEEE 802.16 framework. This standardisation effort is focussed on wireless metropolitan-area-networks (WMANs). The initial application was for point-to-point links, with a main focus on providing a cost effective alternative for the wired local-loop. These systems [9] are often collectively referred to as WiMax and can operate in the 2-11 GHz band, providing speeds up to 75 Mb/s. The bandwidth is flexible, varying from 1.5 - 20 MHz. The system provides an OFDM and OFDMA mode with 256 and 2048 subcarriers, respectively.

Recently, an extension to this standard was proposed which extends the application of these systems to mobile networks. This extension of focussed on frequency bands below 6 GHz and applies a scalable OFDMA design. Again the bandwidth is flexible, but at a bandwidth of 5 MHz a maximum data rate of 15 Mbit/s can be achieved. This design is being standardized as IEEE 802.16e and a version is currently being deployed in Korea as Wireless Broadband (WiBro).

III. Phase noise

As mentioned in the introduction of this paper, OFDM based systems are very vulnerable to radio front-end induced impairments. The imperfections of the radio frequency (RF) oscillator are treated

here, since these have been identified as the major performance limiting factors of OFDM systems. First Section III-A treats the influence of imperfect oscillators on the OFDM signals and then several digital compensation techniques for this influence are reviewed in Section III-B.

A. Influence of Phase Noise

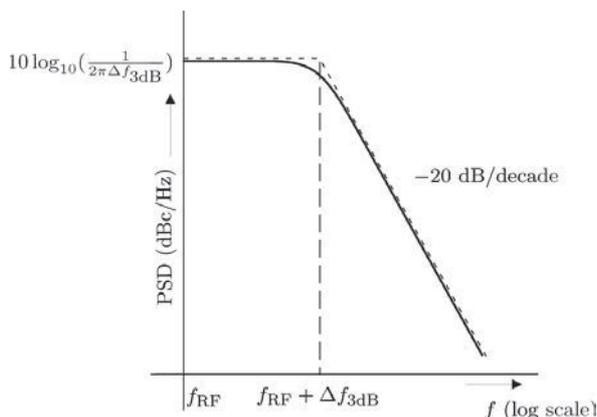
Ideally an RF oscillator would exhibit a power-spectral-density (PSD), which resembles a delta-function at frequency f_{RF} . Any practical oscillator, however, experiences disturbances due to thermal noise, making the PSD differ from the ideal. Since in general the disturbance of the amplitude of the oscillator output is marginal [10], [11], most influence of the oscillator imperfection is noticeable in random deviation of the frequency of the oscillator output. These frequency deviations are often modelled as a random excess phase, and therefore referred to as *phase noise*. Phase noise (PN) will more and more appear to be a factor limiting the performance of OFDM systems, when low-cost implementations or systems with high carrier frequencies are regarded [12], since it is in those cases more challenging to produce an oscillator with sufficient stability.

The RF oscillator process used for down-conversion of the received signal can be modelled as

$$a(t) = e^{-j\{2\pi f_{\text{RF}} t - \theta(t)\}} \quad (1)$$

where j denotes the imaginary unit, t is the time variable and $\theta(t)$ denotes the PN process. When (1) models a free-running oscillator it can be shown that the corresponding PSD is given by the Lorentzian function [11], as depicted schematically in Fig. 9. The PN process is then fully determined by the 3 dB bandwidth $\Delta f_{3\text{dB}}$ of the PSD.

Fig. 9. Single side band representation of the PSD of the oscillator process centred around f_{RF} .



If we, subsequently, regard the influence of PN on the reception of the OFDM symbols, we find that the time domain signal in the baseband receiver is multiplied with the phase noise process $e^{j\theta(t)}$. In the frequency domain this can be seen as a convolution of the OFDM subcarriers, as depicted in Fig. 2, with the PSD of the oscillator process, as depicted in Fig. 9. Clearly this degrades the orthogonality between the subcarriers.

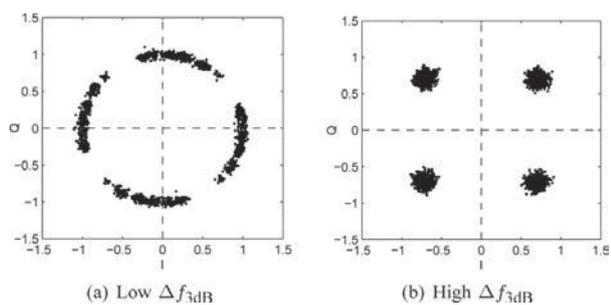
The received signal, behind the DFT-processing in the RX, on the k th carrier of the m th symbol is then given by

$$x_m(k) = e^{j\alpha_m} H_m(k) + \xi_m(k) \quad (2)$$

where $s_m(k)$ and $H_m(k)$ denote the transmitted symbol and channel response on the k th carrier of the m th symbol, respectively. The effects of the PN are modelled in a phase rotation common to all carriers, i.e., α_m and the parameter modelling the leakage into carrier k th, i.e. $\xi_m(k)$. The latter is often referred to as inter-carrier-interference (ICI) and consists of a weighted sum of the received symbols on all other subcarriers. The phase rotation $e^{j\alpha_m}$ is given by the average value of $e^{j\theta(t)}$ during the m th symbol.

This influence of PN on the received signal in an OFDM system applying QPSK modulation is illustrated in Fig. 10. These results are for a system transmitting several packets and not experiencing a channel, i.e., $H_m(k) = 1$ for all k and m . In Fig. 10(a) a typical result is shown for a system having an oscillator characterised by a corner frequency $\Delta f_{3\text{dB}}$ which is low compared to the spacing of the subcarriers. It can be concluded that the dominant effect of PN is the rotation. When $\Delta f_{3\text{dB}}$ is increased, whereas the total noise power remains unchanged, for the situation in Fig. 10(b), the rotational behaviour is less pronounced, but a higher additive behaviour is visible.

Fig. 10. Influence of PN on the reception of QPSK symbols.



It can be concluded from Fig. 10 that the lower and higher frequencies in the PN PSD result in rotational and additive behaviour, respectively. For more indepth information on this behaviour and the influence of PN on the system performance in general, the reader is referred to [13–15].

B. Suppression of Phase Noise

Designing an oscillator with high enough stability to overcome the effects presented in Section III-A is very challenging, especially when low-cost solutions are regarded. In contrast, here we regard the compensation of these effects by the use of signal processing in the digital baseband part of the RX.

Different approaches have been proposed in the literature to remove this rotational part. The techniques can basically be divided into two groups, where the first one uses a dataaided approach and the second one uses detected data-symbols to estimate α_m . For an example of the former the reader is referred to [14]. Basically these techniques exploit that known symbols $s_m(k)$, i.e., pilot symbols, are transmitted on certain subcarriers. Since the rotation is common to all carriers, the location of these pilot carriers is not important, but they are generally equally spaced over the whole system bandwidth, to avoid that all pilots would fall in a channel fade. The second group of techniques first compensates the received signal for the estimated channel response and α_{m-1} , which was estimated in the previous symbol. Now, the average rotation of this corrected symbol gives an estimate of $\Delta\alpha_m$, which provides the estimate of $\alpha_m = \alpha_{m-1} + \Delta\alpha_m$.

Next to the compensation of the rotational part, also suppression of the PN-caused ICI component $\xi_m(k)$ is possible. Recently, some approaches have been proposed for this ICI compensation [16], [17]. These techniques use that the ICI at a certain carrier is dominated by the neighbouring carriers. Some gain in performance is achieved here, but the overall effect is limited at low SNRs and in fading channels.

IV. IQ Imbalance

In this section we discuss the influence of a mismatch between the I and Q branch, known as IQ imbalance. This mismatch occurs due to limited accuracy in the implementation of the RF front-end and results into a limited image rejection. Although IQ imbalance can occur in any quadrature receiver, we here focus on a homodyne receiver [18], as illu-

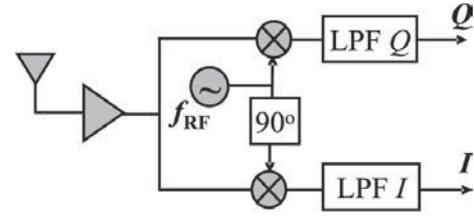


Fig. 11. Schematic representation of a direct conversion based RX.

strated in Fig. 11. The advantage of these direct conversion type of RXs is that no costly surface acoustic wave (SAW) filter is necessary, only two low-pass filters (LPFs), which can more easily be integrated.

First we will regard the influence of IQ imbalance in Section IV-A and then review several digital compensation approaches in Section IV-B.

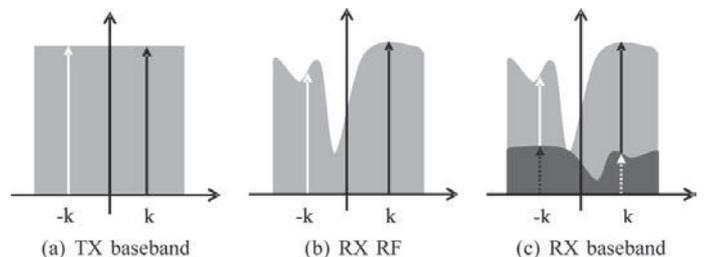
A. Influence of IQ imbalance

The IQ imbalance in the structure of Fig. 11 has several sources, but regarding the influence we can distinguish between two types of IQ imbalance: frequency independent and frequency selective IQ imbalance. An example of the first group is the mismatch which occurs when the phase shift between the signal used for up/down-conversion of the I and Q signal is not exactly 90 degrees. The frequency selective IQ imbalance for instance occurs due to a mismatch between the low-pass filters (LPFs) in the I and Q branches, see Fig. 11. In a practical RX the frequency independent behaviour will be dominant. Hereto, we will focus on this behaviour here.

The influence of IQ imbalance is shown schematically in Fig. 12. The transmitted baseband signal is shown in Fig. 12(a), where two carriers ($-k$ and k) are highlighted.

These carriers have the same separation from DC. The signal is up converted to RF and transmitted to the frequency selective channel, where the received RF signal is depicted in Fig. 12(b). It is clear that car-

Fig. 12. The influence of the IQ imbalance on the reception of an OFDM signal.



rier $-k$ is more attenuated by the channel than carrier k . Subsequently, the RX signal is down converted to baseband using the homodyne structure of Fig. 11. Since this structure exhibits IQ mismatch, the mirror is not fully rejected, and mixes down into the regarded baseband channel. This is illustrated in Fig. 12(c), which shows that carrier k experiences a contribution of the signal received on the mirror carrier $-k$ and vice versa.

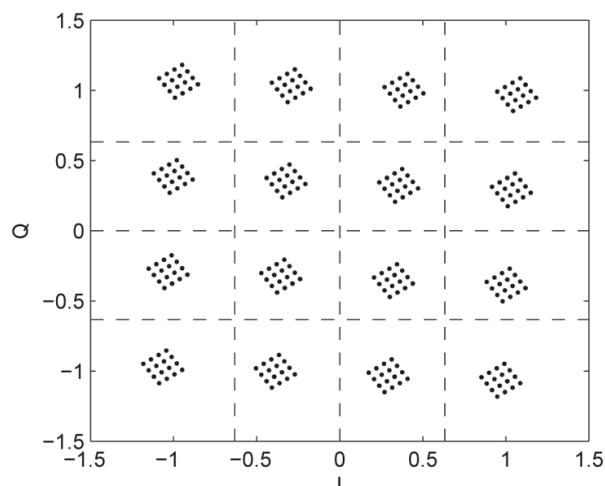
The effect on the received baseband signal can be expressed as

$$x_m(k) = K_1 H_m(k) s_m(k) + K_2 H_m^*(-k) s_m^*(-k) \quad (3)$$

where $*$ denotes complex conjugation and K_1 and K_2 model the imbalance. The effect of mirror leakage as shown in Fig. 12(c) is also apparent from (3). In general K_1 is larger than K_2 and in a system with ideal matching $K_1 = 1$ and $K_2 = 0$.

To clearly show the effect of the IQ imbalance on the reception of an OFDM signal, a noiseless system applying 16QAM modulation is regarded. The system does not experience a wireless channel, but has a 10% amplitude and 5° phase imbalance between the I and Q branches of the RX. The received signal is depicted in Fig. 13, which shows that the transmitted 16-QAM points are distorted by an additive rotated 16-QAM constellation of lower amplitude. This is due to the leakage of the mirror carrier $-k$, where the rotation and reduced amplitude are due to the imbalance parameter K_2 . Furthermore, one may observe a minor rotation and decrease in amplitude due to the multiplication of the desired signal (on carrier k) with imbalance parameter K_1 .

Fig. 13. Influence of IQ imbalance on the reception of 16-QAM symbols in a noiseless channel-less scenario.



B. Suppression of IQ imbalance

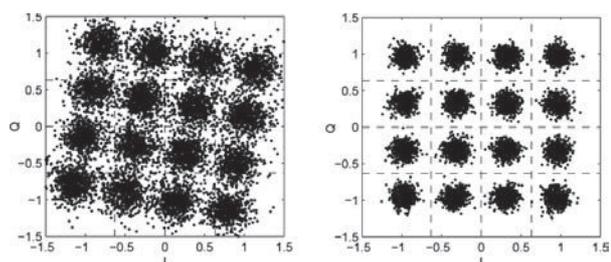
The occurrence of IQ imbalance can be circumvented by increasing the accuracy of the implemented mixing structure, which would result into a more expensive solution. The use of compensation techniques for this RF impairment is, however, promising, since the IQ imbalance variation with time is negligible and the influence of IQ imbalance has a very specific structure, as was shown in Section IV-A.

Several compensation approaches have been proposed for the compensation of IQ imbalance, mainly focussing on imbalances in the RX. Again data-aided and blind techniques can be distinguished. An effective data-aided technique was proposed by the authors of [19], which is applicable for systems applying a block of pilot carrier preceding the data carriers. It applies the fact that the estimate of the wireless channel will not be smooth, when IQ imbalance occurs in the down conversion. A blind method was proposed by the authors of [20], where the imbalance parameters are estimated by using the statistical independence of the data symbols transmitted on carrier k and $-k$. Both methods can be applied to significantly suppress the RX based IQ imbalance.

When the system, however, experiences both TX and RX IQ imbalance, these techniques will not suffice. Therefore, the authors recently proposed a data-aided approach for joint estimation of TX and RX induced IQ imbalance [21]. This method effectively compensates for the joint TX and RX IQ imbalance in the digital baseband part of the RX.

An example of results achieved with the blind compensation method for RX IQ imbalance [20] is shown in Fig. 14. Here a scenario with severe RX imbalance and experiencing additive RX noise is regarded. It is clear from Fig. 14(a) that detection of the receiver 16-QAM points before digital compensation would result in many errors. The results after the compensation are shown in Fig. 14(b). It

Fig. 14. Effects of IQ imbalance compensation.



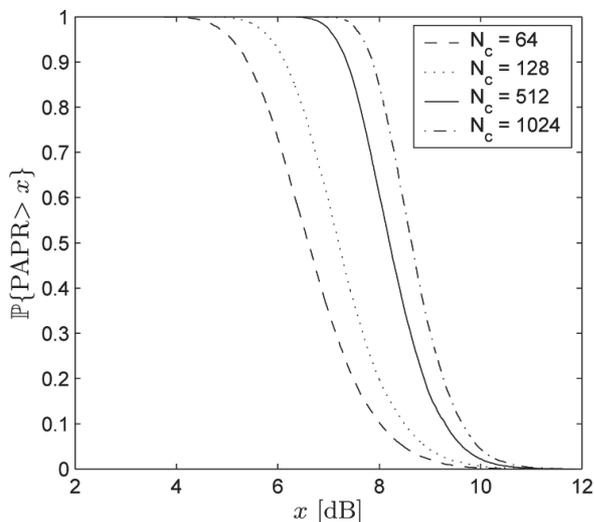
can be concluded that the rotation and attenuation of the signal (by K_1) has been successfully removed. Furthermore, the scatter plot of the constellation points are much smaller after compensation, showing that also the mirror leakage is removed. The remaining impairment is due to the additive RX noise.

V. Nonlinearities

One of the major drawbacks of an OFDM system over a single-carrier system, is that the time-domain OFDM signal exhibits a large peak-to-average-power ratio (PAPR), which, as will be shown in Section V-A, requires a highly linear system. The PAPR is dependent on the order of the applied modulation scheme and the number of subcarriers. If the number of subcarriers N_c or the M -QAM modulation order increases the PAPR becomes higher. Figure 15 illustrates the PAPR dependence on N_c for a system applying 64-QAM modulation. It, hereto, shows the inverse cumulative distribution function for the PAPR of the OFDM-symbols for different number of subcarriers, which indicates the chance that the PAPR is larger than the value on the x-axis.

It can be concluded from the figure that for 1024 subcarriers 50% of the symbols possesses a PAPR which is higher than 9 dB. This would not be a disadvantage in a fully linear wireless system. Any practical system, however, has nonlinear parts like for instance the power amplifier (PA) in the TX and low-noise amplifier (LNA) in the RX. The influence of these nonlinearities on the signal is discussed in Section V-A and suppression approaches are reviewed in Section V-B.

Fig. 15. PAPR of 64-QAM OFDM symbols for different number of subcarriers N_c .



A. Influence of Non-linearities

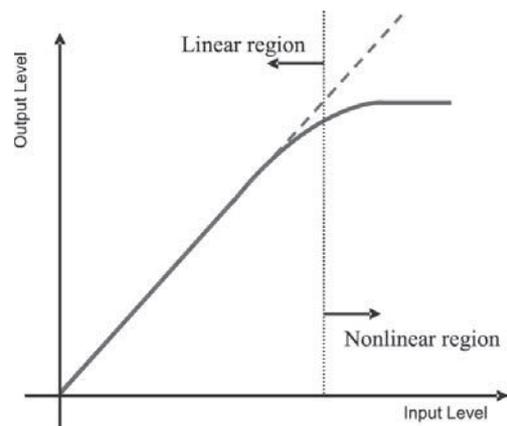
For illustration purposes Fig. 16 schematically depicts the transfer of a nonlinear PA. It shows that the PA delivers linear amplification for input powers up to a certain level. Beyond this level the amplification decreases compared to the linear curve. When the input power is even higher clipping occurs, i.e., the output power is limited to the maximal output power of the PA.

To minimize the influence of nonlinearities and clipping, we would like to locate the signal in the linear region. This linear region is bounded by the point where the transfer deviates 1 dB from the linear response, i.e., the 1 dB compression point. Although Fig. 16 shows the nonlinear transfer of the amplitude, often referred to as AM-AM transfer, also AM-PM behaviour occurs, i.e., phase deviations occur at high input levels. In the remainder of this section we will focus on the former.

When transmitted in the nonlinear region of the system, the time-domain signal will be distorted. This will result in a two-fold behaviour. First, in-band distortion of the detected signal occurs, since the nonlinearities basically destroy the orthogonality between the carriers, which decreases the system performance. Furthermore, these nonlinearities introduce out-of-band leakage due to spectral regrowth, i.e., the transmission levels in neighbouring bands are increased. Since the allowed transmit powers in neighbouring bands are limited by regulations, this poses a problem for the overall system design.

An example of the first effect is shown in Fig. 17, where a received 16-QAM modulation is shown for

Fig. 16. Transfer of a nonlinear power amplifier.



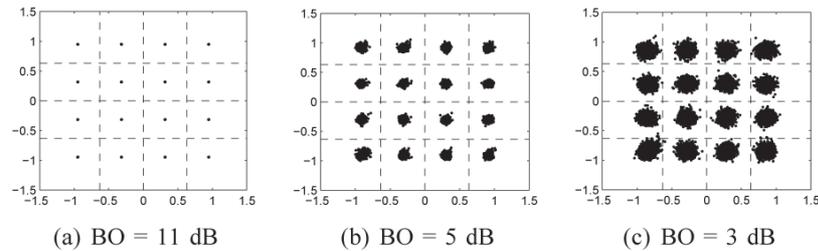


Fig. 17. The effects of a nonlinear PA on the received constellation for different BO values.

a 64 subcarrier OFDM system having a nonlinear PA, where the AM-AM distortion is modelled like in [22]. Again a channel-less and noiseless scenario is assumed. The signal is fed at different levels to the PA. Hereto an back-off (BO) is applied, which is the difference between the average input power level and the input power corresponding to the border between the linear and nonlinear region. The higher the BO is the more linear the transfer is that the signal experiences, but also the lower the output power becomes.

It can be concluded from Fig. 17 that for a BO of 11 dB almost no influence of the nonlinearities is visible. This can be explained by the fact that the chance that the PAPR is larger than 11 dB is smaller than 10^{-4} . It is thus very unlikely that one of the peaks falls in the nonlinear region. This is different for smaller values of BO, as is clear from Fig. 17(b) and Fig. 17(c), where a growth of the scatter points is observable, which corresponds to an increased probability of erroneous detection of the transmitted symbols.

B. Suppression of Non-linearities

The conventional method to overcome the influence of nonlinearities, by applying a BO, reduces the output power and is, thus, very energy inefficient. Therefore, different signal processing techniques were proposed to overcome this problem. The approaches can be split into techniques which try to reduce the PAPR of the signal and techniques that try to compensate for the nonlinear behaviour.

Several techniques have been proposed of the last few years to reduce the PAPR of an OFDM signal. The use of complementary block codes for this purpose was proposed in [23]. The authors of [24] propose a technique named selected mapping, where different codes words are generated representing the same data. The codeword resulting into the lowest PAPR is then selected and transmitted. The use of linear combination of partial transmit

sequences was proposed in [25]. In this approach blocks of carrier are multiplied with different phase shifts. The combination of phase shifts that results in the lowest PAPR is selected and the resulting symbol is transmitted. It is noted that the last two techniques require some extra information to be transmitted, i.e., which codeword or combination of phase shifts is used, and reduce the effective datarate in that way. By decreasing the PAPR the system can apply a lower BO and thus operate more efficient.

Linearisation techniques can be applied in both TX or RX of the OFDM system. When it is placed in the TX it is often referred to as digital predistortion. In this technique the TX signal is multiplied with a transfer, which compensates for the nonlinear characteristic of the PA. The combination of their transfers results into a linear transfer up to the point where the PA output power is maximum, where the clipping will again occur. This is illustrated in Fig. 18. The linearisation can be implemented in different ways: one option is to estimate the nonlinear characteristic in an offline calibration mode and another option is the use of an adaptive algorithm. For more information on digital predistortion the reader is referred to [26].

Although compensation for the nonlinearities generally is done at the TX, it can also be carried out at the RX, enabling joint compensation of the nonlinearities throughout the transmission chain. The disadvantage is that it does not help to decrease the out-of-band radiation, but it does enable the correction for clipped signals, decreasing the probability of erroneous detection.

The individual techniques highlighted in this section might require a considerable complexity in the baseband part of the wireless system to significantly reduce the performance degradation due to non-linearities. However, when combinations of

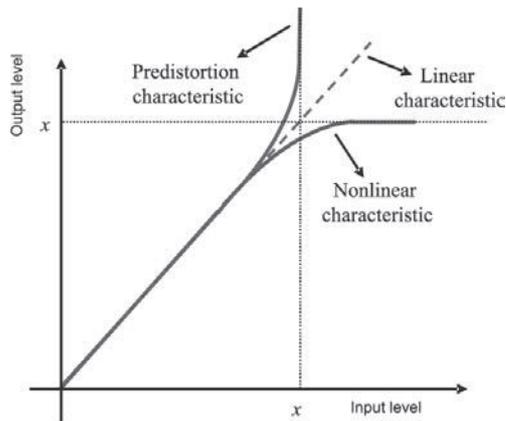


Fig. 18. Nonlinear and predistortion characteristics.

the different techniques are applied, the complexity can be minimized.

VI Conclusions

The applications multiple carriers can effectively be used to overcome the impact of multipath propagation on the performance of wireless systems applying high bandwidths. The most applied multi-carrier technique is orthogonal frequency division multiplexing (OFDM). It is shown that OFDM effectively divides the frequency selective channel into frequency flat parallel subchannels. The addition of a guard interval to the OFDM symbols removes the influence of inter-symbol interference. Furthermore, the application of channel coding, OFDMA and adaptive modulation turn the time dispersive channel into an advantage, by exploiting the provided frequency diversity. This is the reason why the application of OFDM is proposed for use in many wireless systems over the last few years.

It is also explained that OFDM is sensitive to imperfections in the analogue front-end of the transmitter and receiver. It is shown that phase noise, IQ imbalance and nonlinearities impose severe performance degradations to an OFDM system. This paper, however, also highlights that the application of digital signal processing can largely overcome these disadvantages. A design incorporating these digital compensation techniques allows for higher impairment levels, and thus opens the door for cheaper and more optimized implementation of the RF front-end.

Overall it can be concluded that multi-carrier techniques are a natural choice for wideband systems to be applied in multipath environments, especially

since its major drawbacks can largely be solved by emerging digital compensation techniques.

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Rectenna design for wireless power transmission - An analytical approach

J.A.G. Akkermans
October 31, 2005

Introduction

The use of electromagnetic radiation to provide wireless power transmission can be a useful solution for applications which need a long-term power supply. The increasing number of wireless applications only increases this demand. This article focuses on the realization of a practical implementation for wireless power transfer. Electromagnetic energy is received through an antenna. After that, the received energy is converted to electric power for our application by a rectifying circuit (Figure 1). Because of the combination of antenna and rectifying circuit the system is often referred to as 'rectenna'. The challenge in our research is to create a rectenna which has an efficient conversion of the received RF energy to useful electric power.

In general, wireless low-power applications have small dimensions. Often, this is one of the strong points of the application. Therefore a rectenna with limited dimensions is advantageous. Another important requirement of the rectenna is its conversion efficiency. The amount of received energy that is converted to usable power should be as high as possible. Especially for low-power environments, where the amount of received energy is limited, the importance of an efficient conversion is high. A third requirement for the rectenna is that it provides a stable output power. Low-power applications often contain integrated circuits which need a stable power supply to operate properly.

The practical model that we would like to design is used in the frequency range from 2.40-2.48 GHz. This is a frequency band where license-free opera-

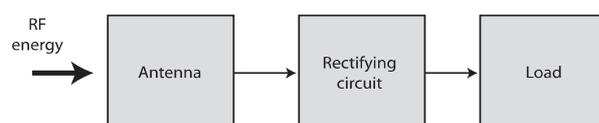
tion is permitted. Wireless power transfer systems often use this frequency band, owing to the low losses in the atmosphere for electromagnetic radiation in this frequency band. Another advantage is the availability of cheap components for these frequencies. The maximum amount of radiated power that is allowed in this frequency band is 100 mW in The Netherlands [1]. For other countries, other regulations may apply. In general, only a small portion of the transmitted energy is received by the rectenna. For our practical model, we assume a received power level of 1 mW. Although this choice is somewhat arbitrary, it lies within the range of expected power levels for our applications.

The antenna and rectifying circuit have to be modeled at and around the operating frequency. The rectenna is modeled via analytical expressions. The advantage of analytical expressions is that they often give a good insight in the physical behavior of the system. Sub-circuits of our rectenna, e.g. the antenna, can also be simulated via numerical full-wave simulations. This can lead to more accurate results, at the cost of a significantly larger computation time. Therefore we will start with an analytical approach. Throughout the whole design process the analytical models will be verified with measurements. In the following sections the analytical models for the antenna and rectifying circuit will be derived. Finally, these models are combined for the design of a rectenna.

Antenna

A probe-fed patch antenna is utilized as antenna. The advantages of this type of antenna are its ease of manufacturing and its compact dimensions. Within the antenna, the electric fields are perpendicular to the upper and lower conducting planes. Near the edges of the patch the fields will bend a little outwards (Figure 2). These so-called 'fringe fields' cause the microstrip antenna to radiate.

Figure 1: Schematic rectenna system.



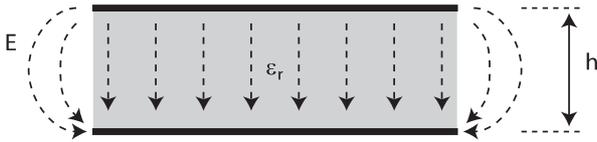


Figure 2: Fringe fields of the patch antenna.

The patch antenna can be modeled analytically with the cavity model [2]. In this model, the fringe fields at the edges of the patch are ignored, thus imposing perfect magnetic boundaries at the side walls of the antenna. This assumption is valid for small heights of the dielectric. It allows us to write the field inside the cavity as a sum of modes for patches with a simple geometry (e.g. rectangular, circular).

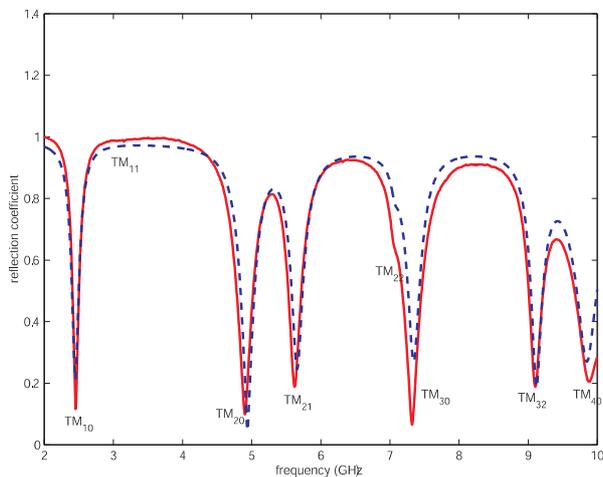
$$\vec{E}(\vec{r}) = \sum_m \sum_n a_{mn} \phi_{mn}(\vec{r}) \quad (1)$$

here ϕ_{mn} represents a basis function that describes the field distribution for the mode mn and a_{mn} is an amplitude term. Additional losses are introduced to account for radiation, metallic and dielectric losses. Effective patch dimensions are used to accurately predict the resonance frequency of the antenna. The validity of the cavity model is checked with a measurement of a patch antenna for a wide frequency range (Figure 3).

Rectifying circuit

The received RF power from the antenna has to be converted to DC power by a rectifying circuit. In this way, we are able to pass the received power to the application which we want to supply with electric energy. Obviously, we would like to convert as

Figure 3: Reflection coefficient rectangular patch antenna, length = 29 mm, width = 29 mm, thickness substrate = 1.6 mm, $\epsilon_r = 4.28$, $\tan \delta = 0.02$. Measurement (solid) and model (dash).



much of the RF power to DC power as possible. Therefore it is important to accurately model our rectifying circuit, such that we are able to achieve an efficient conversion.

The main component of the rectifying circuit is the Schottky diode, which is modeled by the electric circuit shown in Figure 4. The model for the Schottky diode consists of a substrate resistance R_s , a junction capacitance C_j , which is assumed to have a linear voltage-current relation, and a nonlinear diode D , which has a voltage-current characteristic given by

$$i_D = I_s (e^{\alpha v_D} - 1) \quad (2)$$

here i_D is the current through the nonlinear diode, v_D is the voltage over the nonlinear diode, I_s is the saturation current and $\alpha = \frac{q}{nkT}$ is the reciprocal of the thermal voltage. Here q is the charge of an electron, T is the temperature in Kelvin and n is the diode ideality factor.

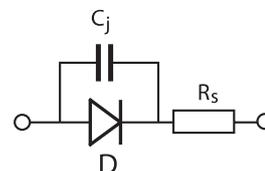
During stationary operation, the current through the nonlinear diode can be represented by a sum of harmonics, i.e.,

$$i_{hN} = i_0 + \sum_{n=1}^N [\kappa_n \cos(n\omega_0 t) + \zeta_n \sin(n\omega_0 t)] \quad (3)$$

here i_0 represents the direct current and κ_n , ζ_n represent the amplitudes of the harmonic terms, operating at the radial frequency $n\omega_0$. For each of the harmonic terms, the equivalent Thévenin circuit of the linear circuit is determined. If the current i_h is given, the voltage at the output of the linear circuit is known. This voltage is used to determine the current i_D through the diode. Since the current at the output of the linear network is equal to the current through the diode, we can find the coefficients κ_n and ζ_n by minimizing the square of the error ϵ between i_D and i_{hN} over one period of time T [3], i.e.,

$$\epsilon = \frac{1}{T} \int_0^T [i_D - i_{hN}]^2 dt \quad (4)$$

Figure 4: Electric circuit for the Schottky diode.



The coefficients κ_n , ζ_n can be found via a multi-dimensional minimization method, e.g., a simplex method [4].

Once the coefficients κ_n and ζ_n are known, the input impedance of the diode can be determined. The number of harmonics N that should be taken into account to obtain an accurate input impedance depends on the signal level. For large signals, more harmonics should be taken into account than for small signals, since the nonlinearity of the diode has a larger impact for these signals.

If it is allowed to consider only a limited number of harmonics N , we can find an analytical expression for Eq. (4). In the simplest case, only the DC term of the current is determined. For this case, a closed-form algebraic relation between input voltage and DC input current can be found [5]. In our case, this analysis is not sufficient, since it does not give an expression for the input impedance of the diode at RF frequencies. Therefore we have to include at least one harmonic term ($N = 1$)

$$i_{h1} = i_0 + \kappa_1 \cos(\omega_0 t) + \sigma_1 \sin(\omega_0 t) \quad (5)$$

The voltage over the diode D in the time domain can be modeled using Thévenin's theorem as

$$v_{D1} = a \cos(\omega_0 t) + d \sin(\omega_0 t) - R_g i_{h1} - X_g \frac{\partial}{\partial t} i_{h1} \quad (6)$$

Here, a and b determine the amplitude and phase of the equivalent Thévenin voltage source. R_g and X_g determine the output impedance of the source, where R_g represents the resistance and X_g is a measure for the inductance or capacitance. The resulting error term is given by

$$\begin{aligned} \epsilon_1 &= \frac{1}{T} \int_0^T [I_s (e^{\alpha v_{D1}} - 1) - i_{h1}]^2 dt, \\ &= \frac{1}{T} \int_0^T I_s^2 e^{2\alpha v_{D1}} - 2(I_s - i_{h1}) I_s (e^{\alpha v_{D1}} + (I_s + i_{h1})^2) dt \end{aligned} \quad (7)$$

The closed-form solution of this integral can be found in [6, Eq. 3.937] and is given by

$$\begin{aligned} \epsilon_1 &= I_s^2 e^{-2\alpha i_0 R_g} I_0(2\alpha \sqrt{p^2 + q^2}) \\ &\quad - 2(I_s + i_0) I_s e^{-\alpha i_0 R_g} I_0(\alpha \sqrt{p^2 + q^2}) \\ &\quad - 2I_s e^{-\alpha i_0 R_g} \frac{\kappa_1 p + \sigma_1 q}{\sqrt{p^2 + q^2}} I_1(\alpha \sqrt{p^2 + q^2}) \\ &\quad + (I_s + i_0)^2 + \frac{1}{2}(\kappa_1^2 + \sigma_1^2) \end{aligned} \quad (8)$$

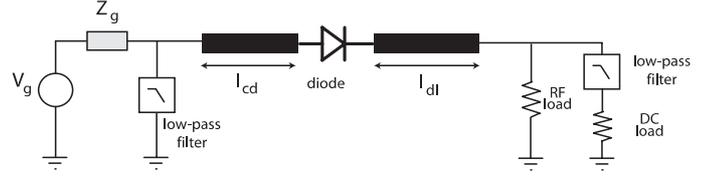


Figure 5: Measurement setup for the Schottky diode.

with

$$\begin{aligned} p &= a - \kappa_1 R_g - \sigma_1 \omega X_g \\ q &= b - \sigma_1 R_g + \kappa_1 \omega X_g \end{aligned} \quad (9)$$

here, I_0 and I_1 are the modified Bessel functions of the first kind of order 0 and 1, respectively.

When higher harmonics ($N > 1$) have to be taken into account, the integral of Eq. (4) is evaluated numerically.

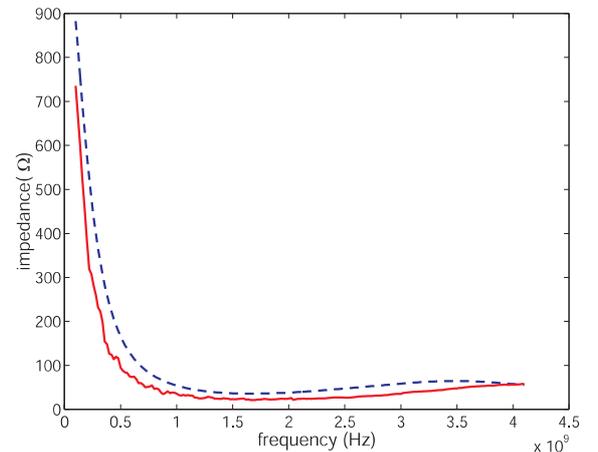
To validate the presented approach, a Schottky diode is measured. The diode is mounted on a transmission line and measured with a network analyzer. The measurement setup is shown in Figure 5. The measured and modeled input impedance is presented in Figures 6 and 7. For the simulations three harmonic terms are taken into account.

Rectenna

The main design parameters of the rectenna are the dimensions and the conversion efficiency. To acquire a small-area rectenna, a layered design is proposed.

The backside of the patch antenna is used for the rectifying circuit. As a result, the ground plane of the antenna is used as a ground plane for the rectifying circuit as well. The conversion efficiency η is

Figure 6: $\text{Re}\{Z_{in}\}$ diode circuit. Measurement (solid) and model (dash)



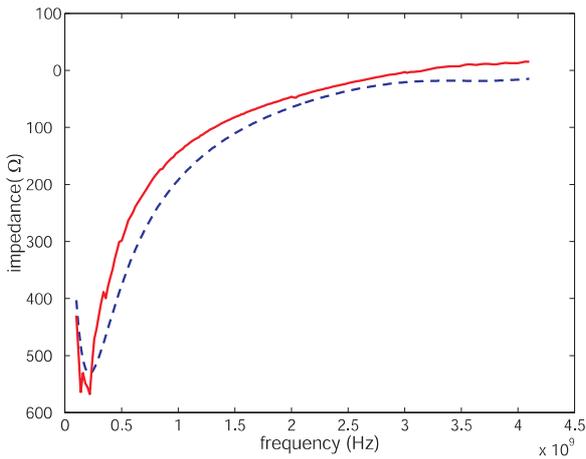


Figure 7: $Im\{Z_{in}\}$ diode circuit. Measurement (solid) and model (dash)

defined as the ratio of DC power to received power, i.e.,

$$\eta = \frac{P_{DC}}{P_{inc}} \quad (10)$$

In our design, additional radial stubs are placed between the antenna and the rectifier to prevent the first harmonic from being reradiated by the antenna. This is necessary because the harmonics of the operating frequency correspond closely to radiating modes of the patch antenna. Higher harmonics are excited as well, but not as significant as the first harmonic. The filter structure between the antenna and the rectifying circuit can be simplified when the harmonics generated by the rectifier do not correspond to radiating modes of the antenna. This property is employed in [7], where circular patch antennas are used.

Between the rectifier and the load also two radial stubs are placed. One radial stub prevents the signal at the operating frequency from being dissipated in the load and one radial stub prevents the signal at the first harmonic frequency from being dissipated.

The analytical models are employed to acquire a match between microstrip patch antenna and the rectifying circuit, including the radial stubs. The conversion efficiency is increased by choosing a probe position that corresponds to a high output impedance of the antenna. In this way the output voltage of the antenna increases for the same incident power level, which is favorable for the conversion efficiency of the Schottky diode.

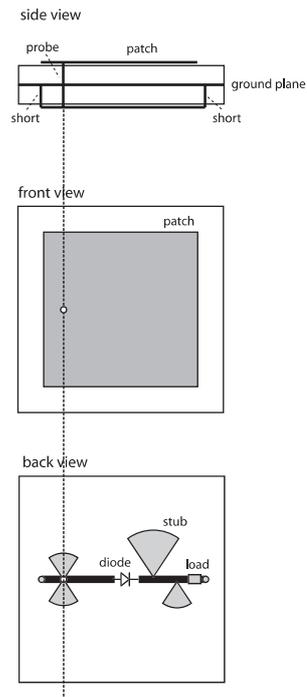


Figure 8: Layout of the stacked rectenna.

The layout of the rectenna is given in Figure 8. The layered rectenna is photo-etched from copper-clad FR4 material, which allowed for a fast realization of the product (Figure 10). To model the DC output voltage, the incident power received by the patch antenna is measured for a fixed transmit-receive setup. This data is used in the model to predict the DC output voltage of the rectenna. The result is shown in Figure 9. The conversion efficiency η equals 40%. This is comparable to the efficiency of 50% presented in [8].

Figure 9: DC output voltage of the stacked rectenna. Measurement (solid) and model (dash).

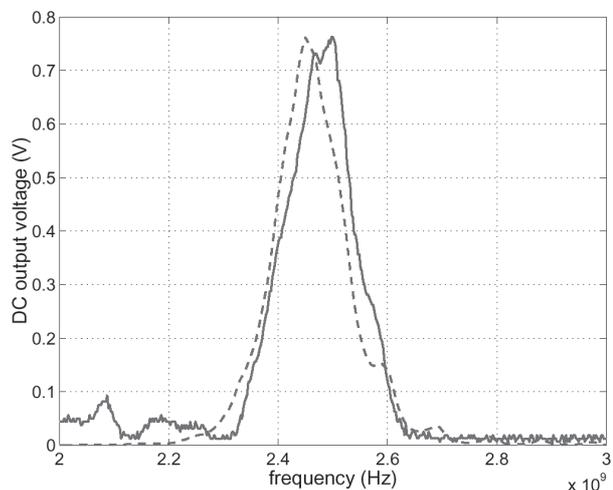




Figure 10: Realization of the rectenna on FR4

Conclusions

This article presents the implementation of a rectenna for wireless power transmission. The conversion efficiency is comparable to results presented in literature. It is shown that the behavior of the rectenna can be modelled accurately with analytical models. These models allow for a fast design of rectenna systems and enable an optimization of the rectenna layout for a large number of parameters.

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