RADIO OVER FIBER FOR WIRELESS COMMUNICATIONS
From Fundamentals to Advanced Topics
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FROM FUNDAMENTALS TO ADVANCED TOPICS

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About the Author

Xavier Fernando is a Professor at Ryerson University, Toronto, Canada, where he is serving as the Director of Ryerson Communications Laboratory. He earned his Ph.D. from the University of Calgary, Alberta, in 2001 in affiliation with TRLabs, a not-for-profit telecom research institution. He was among those who pioneered research on optical fiber-based wireless systems in the late 1990s. His Ph.D. work in this area – where he first investigated adaptive digital signal processing (DSP) techniques for fiber-wireless (Fi-Wi) systems – won the best Canadian paper award and a US patent. He joined Ryerson University in 2001, received early tenure, and established Ryerson Communications Laboratory.

Xavier has published his research articles in multiple frontiers of Fi-Wi systems, from signal processing for (radio-over-fiber) ROF nonlinearity to microwave photonic filter design. He has received significant funding for research in this area. He has authored and co-authored close to 100 research articles and holds two patents. He is a co-author of WEBOK, A Guide to the Wireless Engineering Body of Knowledge.

Xavier was a member of the IEEE COMSOC Education Board Working Group on Wireless Communications. His work has won several awards and prizes, including the IEEE Microwave Theory and Techniques Society Prize in 2010, the Sarnoff Symposium Prize in 2009, the Opto-Canada best poster prize in 2003, and the CCECE best paper prize in 2001. He has delivered invited lectures and tutorials worldwide. He is a program evaluator for ABET and the General Chair for the IEEE Canadian Conference on Electrical and Computer Engineering (CCECE 2014). He was a member of the Ryerson Board of Governors in 2010–2011 and the Chair of the IEEE Toronto Section in 2012–2013.
Foreword

Just consider how much our lives today are influenced by wireless and mobile communication technologies: from synchronized calendars to emails on the go, from simply browsing the Internet to uploading high-definition videos and photos taken with mobile phones to Facebook, from accessing maps and navigation advice to being entertained with high-definition television and videos; smart phones with mobile and Wi-Fi enable us to live our lives to their full potential. As this mobile data consumption grows and more and more machines and devices begin to incorporate the same communication platforms to achieve high-bandwidth communication via wireless channels, the networks that provide connectivity need to change by first providing more bandwidth to more users over ever growing geographic areas. The combined effect of growing data bandwidth and the ever-growing number of devices is poised to create a massive challenge in designing, building, and operating future broadband wireless access networks. Reducing the coverage of mobile networks to form small cells, shifting the carrier frequency of radio communications to high frequencies to be able to offer more bandwidths to users, and providing broadband back-haul from base stations are all needed to address this challenge. Radio over fiber (ROF) technology provides a promising technique to combine the advantage of wireless connectivity of a broadband wireless link over short distances with the bandwidth abundance of optical fiber networks in order to address these issues.

This book, entitled Radio over Fiber for Wireless Communications – From Fundamentals to Advanced Topics, is a timely introduction to this important area and the author presents it elegantly through a well-structured book. The book gradually introduces the basic concepts, moving toward a comprehensive treatment of the topic – from transmission basics to advanced modulation methods, from optical links to wireless channels, and from linear to nonlinear impairments and mitigation strategies. Professor Xavier N. Fernando has been at the forefront of ROF research since its early stages and is definitely a leading authority on this topic. Professor Fernando has combined his in-depth understanding and long academic experience to deliver a classic book that gives us a comprehensive look at ROF technology. This book will help to inform engineers and industry practitioners, as well as researchers, with up-to-date coverage of the technology. Professor Fernando should be congratulated for writing this classic text, which I hope will provide further focus on this important technology.

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Preface

First of all, thank you for buying this book. It was a very good decision. You will not be disappointed. As the name implies, the book will first provide a fundamental understanding of the topic for those who are new to it. The book then develops knowledge in advanced topics. The book is written for general communication systems engineers, who may not have detailed knowledge of photonic systems. It covers some design issues from an engineer’s point of view. It also includes ongoing research and recent developments in multiple frontiers of Fi-Wi networks that will be useful for researchers and graduate students.

This book is the culmination of many years of my work in this area. Using photonic technologies for wireless communications first fascinated me during my Master’s studies. I used to dream of combining the benefits of these two systems. My original idea was to stream the light wave directly from fiber (my Master’s thesis was on optical-wireless communications). However, I soon realized the practical limitations of light wave propagation in air and started to research RF over fiber – a slightly more practical method but still with many hurdles.

Today, after having been involved in this area for many years, it is very satisfying to complete this book. The book has a unique flavor. Although it is about radio over fiber and fiber-wireless systems, it is not heavily weighted on the area of microwave photonics. It is intended for typical communication system professionals, who may not have in-depth photonic knowledge. However, photonic professionals will also benefit from this book as it will provide a good systems-level understanding of communication-related issues.

Topics Covered in the Book

Let me say a few words about the topics covered in the book first. This book will provide a detailed study of radio over fiber (ROF)-based wireless communication systems, otherwise called fiber-wireless (Fi-Wi) systems. This is an emerging hot topic, where the abundant bandwidth of optical fiber is directly combined with the flexibility and mobility of wireless networks to provide broadband connectivity.

There are many reasons for the recent high level of interest in Fi-Wi systems:

- The Fi-Wi approach enables rapid, cost-effective deployment of micro/picocellular architecture in wireless networks. This architecture will be an answer to the rapidly increasing spectrum crunch because it will increase wireless network capacity without using additional spectrum.
• Fi-Wi systems support true broadband connectivity because wireless channels will be shorter. This feature will be especially attractive for 5G and beyond wireless networks that promise very high bit rates over the air interface (up to 10 Gb/s). The air interface must be very short at these extremely high bit rates due to a number of fundamental limits.

• An ROF-based Fi-Wi architecture enables centralized processing and adaptive radio resource management. This feature will be very useful in dynamic environments.

• ROF is a strong candidate for millimeter-wave wireless systems as well. Attenuation at the air interface will be very high at millimeter-wave bands. No cable other than fiber can carry millimeter-wave signals with very low loss and distortion closer to the user.

• Fi-Wi networks are capable of supporting multiple RF subcarriers simultaneously, due to their abundant bandwidth. This will be an added advantage.

• The recent maturity in microwave photonic technology has brought down the cost of ROF link elements while improving their performance. This makes Fi-Wi systems even more feasible and attractive.

• There is plenty of fiber in most major cities, along highways and railway tracks. The possibility of using existing dark or dim (partly used) fiber for Fi-Wi systems will further reduce the deployment cost.

However, there are a number of technical issues in Fi-Wi networks that need to be addressed before widespread deployment. The limited power-handling capability, low dynamic range of most optical transmitters, and the fiber itself limit the radio cell size. In contrast, subcarrier-multiplexed ROF systems need a high dynamic range to account for RF signal strength variations. Since the fiber and wireless channels are in series in Fi-Wi systems, noise and loss will be cumulative. Furthermore, nonlinear distortion in the ROF link will be combined with multipath dispersion of the wireless channel. Therefore, channel estimation and equalization will be a complicated task. The combined channel will require advanced signal processing algorithms for estimation and compensation. This is even more challenging in a multiuser environment. Advanced signal processing algorithms are essential to overcome some of these limitations.

About the Book Itself

This book can be ranked as an introductory book in Fi-Wi systems. It was written mainly for graduate students and practising engineers. Owing to the nature of the topics, readers are expected to have a basic understanding of fiber optics and wireless communications to easily follow this book. The book is not intended to teach these topics. However, the basics of the Fi-Wi system and signal processing approaches will be clearly explained.

This book covers a multidisciplinary topic and will act as a bridge between optical and wireless communication domains. In fact, one reason for the lack of literature in this increasingly important area is this multidisciplinary nature. In the increasingly demanding telecommunications profession, engineers are expected to have knowledge of both optical and wireless communications and are expected to design combined or hybrid systems, where the knowledge gained through this book will be an asset.

This book has been written in such a way that both optical and wireless professionals will be able to understand the concepts. Usually, some Fi-Wi issues are better perceived by wireless professionals who are more comfortable in the RF domain. Some other Fi-Wi issues are better
understood by photonic engineers who are more familiar with the optical domain. Some other topics are even better learned by signal processing professionals who model wireless communication systems on baseband and develop appropriate algorithms. This book has been written in such a way that all these professionals will hopefully be able to appreciate the concepts.

The first few chapters are devoted to giving wireless systems designers, students, and researchers a quick but fundamentally correct understanding of ROF systems, their advantages and limitations. The basic characteristics of the link elements are described. Power budget calculation fundamentals are developed. The noise behavior of the ROF link is analyzed, and better expressions are derived for the signal to noise ratios considering both optical and electrical domains. Next, we show how complex it can be analyzing multicarrier ROF systems, because of the complicated nature of a nonlinear noisy medium sequenced with a time-varying dispersive medium.

The latter part of the book is devoted to developing digital signal processing techniques to provide high-quality communication over Fi-Wi channels. Channel estimation and equalization algorithms are developed in these chapters considering multipath distortions and noise. Multiuser CDMA environments as well as OFDM environments are considered for this purpose.

The final chapter provides a history of wireless communications and some guidelines on future systems. The reader will realize that fiber feeders will definitely play a vital role in future wireless communication networks. The emerging digitized ROF approach, which will not have the nonlinearity and cumulating noise issues of the analog ROF system, is something to watch out for. RF over coherent fiber-optic link systems is also becoming more practical due to the advancements in microwave photonics and the maturity of laser technology, which will provide better ROF links.
Acknowledgements

There are so many people who helped me on this book, both directly and indirectly. First, I would like to express my sincere gratitude to Professor Abu Sesay, my PhD research supervisor. The fundamental knowledge I gained to write this book was obtained during my stay at TRLabs and the University of Calgary under his supervision. Also, I would like to thank TRLabs for their generosity in providing research facilities and complete freedom to explore new frontiers.

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Special thanks go to Dr. Dave Irvine Halliday of the University of Calgary who was my first fiber-optic professor, from whom I learned the fundamentals and wonders of fiber optics.

I extend my thanks to Ryerson University for their infrastructure and support. I would also like to thank the IEEE for giving copyright permission to reuse some of my published work in this book.

Finally, I wish to thank my family – my loving wife Ruby and our wonderful children Christma, Jonna, and Kanisha – for their support and encouragement throughout the period when I was involved in writing this book.
1

Introduction

1.1 Motivation

The demand for wireless communication services is increasing steadily. According to an estimate by the Global Technology, Media and Telecom (GTMT) team, the number of global mobile phone users is expected to reach 7.6 billion by 2020, up by 41% from 5.4 billion users in 2011. In other words, wireless user penetration will be close to 99% of the global population in 2020, up from 87% in 2011.

The reason for this increase in demand is twofold. First, there is a sustained increment in the number of subscribers. On top of that, the bandwidth demand of most of these subscribers also shows a rapid increase, at an even higher rate than the increment in number of subscribers. The proliferation of smart phones and tablets that enable multimedia services has led to this trend. For example, the average smart phone usage grew 81% just in 2012. Image transfer and video streaming, as well as innovative cloud services, reach an increasing number of customers. Machine-to-machine (M2M) communications and the rapid emergence of the internet of things (IoT) further contribute to the bandwidth quest. Global mobile data traffic grew 70% in 2012, which was nearly 12 times the size of the entire global Internet in 2000 [1]. In the future, the amount of data traffic will grow at a pace never seen before. Many recent forecasts project mobile data traffic to grow more than 24-fold between 2010 and 2015, and much higher beyond 2015 [2]. To catch up with the need and to remain competitive, network operators need to increase the broadband capability of their networks fast. This poses a big challenge for wireless communication system designers. Researchers have been working on innovative systems that will provide several Gbit/s over the air interface [3].

Typically, the current macro cells with relatively long wireless channels cannot support very high bit rates. It is well known that the distance between a wireless transmitter and receiver will impose an upper limit on the bit rate the channel can support for a given transmission power. Long wireless channels will have high path loss, resulting from free-space loss, shadowing, refraction, diffraction, reflection, and absorption effects limiting the bit rate. Widespread research has shown that at extremely high bit rates (very low energy per bit), the air interface has to be significantly shorter in order to have a reasonable power link budget [4]. The value of the wireless channel path-loss exponent ranges from 1.5 to 4 (where 2 is for propagation in free space and 4 is for relatively lossy environments). In some environments, such as buildings,
stadiums, and other indoor environments, the path-loss exponent can reach values in the range of 4 to 6. In addition, a long air interface would have a long multipath delay spread that would result in higher intersymbol interference or frequency-selective fading.

For these reasons, several solutions are being investigated for future 4G and 5G networks to shorten the air interface and provide broadband services [2]. It is obvious that a large number of radio access points is required to shorten the wireless channels, which is happening in many places. The challenge is to feed these radio access points. Traditionally, point-to-point microwave links have remained a popular choice for interconnecting remote radio access points since they can be deployed rapidly and cost-effectively. However, the rising number of remote access points often associated with broadband wireless access networks has been outweighing these advantages. System designers are looking for new technologies, often by optical means. Free-space optical links are sometimes used as a substitute for point-to-point microwave links. However, too many issues—such as sensitivity to alignment and weather fluctuations—limit the practical usefulness of free-space optical links.

1.1.1 The ROF System

In this book we study the radio over fiber technology as an effective solution for feeding broadband radio access points. ROF refers to the technique by which radio frequency signals are transmitted over optical fiber to provide wireless communication services. Note that ROF is essentially an analog communication scheme, though confusion may arise since wireless links carry digital data. Therefore, it is perhaps more technically precise to define analog optical links as ones where the laser is always on or the optical modulation depth is sufficiently small that small signal analysis of the various link devices is possible. This is in contrast to digital optical links in which the optical modulation depth approaches 100% or the laser is turned on and off depending on the modulating data sequence.

These systems are also called fiber-wireless systems. In Fi-Wi systems, the abundant bandwidth of optical fiber is effectively used to provide broadband wireless access by shortening the wireless channel and bringing the radio signal closer to the user.

An ROF Fi-Wi system is realized by modulating the optical carrier by RF signal(s) belonging to wireless networks. Although RF signal transmission over fiber is done in some other applications such as cable television networks and satellite base stations, the term ROF is used exclusively in connection with Fi-Wi communication systems in the literature. We shall follow the same terminology. A simple ROF Fi-Wi architecture is shown in Fig. 1.1, where the RF signal from a central base station (CBS) first travels via an optical fiber to a remote antenna and then reaches the user via the wireless channel. This order is reversed in the uplink direction. This is a cost-effective way to set up micro/picocellular radio architecture. A number of base stations is replaced by a single central base station and many low-cost radio access points (RAPs).

There are several advantages of ROF transmission for remote microcell set up. One important advantage is that minimal modification is required at the base station since the RF signal is transmitted to the remote antenna as is, after all the signal processing, coding (DSP), and modulation stages. This architecture will also allow the remote radio access point to be a simple and inexpensive module performing electrical-to-optical conversions, optical-to-electrical

\[\text{Note that not all Fi-Wi systems are necessarily ROF systems. There are other ways to deploy fiber feeders as well.}\]
conversions, and related RF or optical processing only. In other words, the RAP need not perform baseband signal-processing or frequency-translation operations. Note that often the RAP needs to be installed in places where space is limited, in addition to being inexpensive.

It is well known that optical-fiber links have enough bandwidth to transmit radio waves up to tens of GHz with little distortion. The fiber also offers very low attenuation (the theoretical lower limit is 0.2 dB/km), which would allow multi-GHz radio signals to be transported over several kilometers with very low loss. In contrast to electrical wires, the loss in the optical fiber is a function of the optical wavelength and does not depend on the frequency of the radio signal being transported. Therefore, due to the abundant bandwidth and frequency-independent low-loss properties, multiple RF carriers can readily be frequency division (or subcarrier) multiplexed and transmitted via a single optical fiber (or a single wavelength). Such an arrangement is shown in Fig. 1.2. The RF-modulated optical signal traveling in the fiber is both immune to and will not cause electromagnetic interference with signals outside the fiber. All these factors make the optical fiber the best unparalleled transportation link for RF signals.

Although there are several advantages of ROF Fi-Wi schemes, a few design issues and technical challenges need to be addressed before widespread deployment of Fi-Wi networks. Some issues are better addressed by wireless engineers in the electrical domain while other issues are better addressed by photonic engineers in the optical domain. However, a basic knowledge of both optical and wireless communication systems is needed to get an overall understanding and superior solutions. This book covers the design issues from a system engineer’s point of view, describing the fundamental elements of an ROF link, how it affects the wireless link performance, and some possible solutions.

Research into ROF Fi-Wi started in the early 1990s to provide wireless access to subway stations. Until recently, Fi-Wi systems had mostly been considered for special areas like tunnels, mines, and subway stations, where outdoor macro radio base stations do not provide
coverage. In addition, crowded places like campus premises, supermarkets, airport concourses, and downtown core areas can also be served cost-effectively by ROF Fi-Wi systems [5].

The real power of the ROF-based Fi-Wi solution to provide rapid wireless access was realized during the Sydney Olympics of 2000. ROF technology was used to rapidly set up a microcellular network for the Olympics venue with more than 500 indoor and outdoor microcells. Three GSM operators shared this infrastructure and multistandard (900 and 1800 MHz GSM bands) radio access was supported in a subcarrier-multiplexed manner. Each remote antenna unit provided up to $0.8 \times 1.8$ km$^2$ coverage area. The network capacity was reallocated dynamically as the crowd moved from stadium to stadium. More than 500,000 wireless calls were made just on the opening day using this ROF infrastructure. Its success demonstrated the potential of ROF systems in mainstream wireless networks. More large-scale projects incorporating ROF technology started to be considered after 2000.

Another large-scale deployment is being investigated by Chinese Telecom’s beyond 3G project, code named FUTURE™. Here, ROF is considered to provide RF access to multiple antenna units providing broadband multiple input, multiple output (MIMO) access [6]. The Korean beyond 3G broadband initiative WiBro™ also considers ROF to support microcells. Samsung™ is investigating ROF to provide broadband access in home networks.

FUTON (an EU Framework 7 project) provides an example of a 4G Fi-Wi radio interface [7]. This project is investigating a distributed broadband Fi-Wi system. It envisages a physical layer with throughput capability up to 1 Gb/s. To achieve this throughput, channel bandwidths up to 100 MHz and modulation levels up to 256-QAM with 2048 subcarrier orthogonal
frequency-division multiple access (OFDMA) are considered. Various MIMO configurations are also investigated. There are several other examples available where ROF Fi-Wi systems are considered for broadband access in large national and international projects.

ROF Fi-Wi system researchers have demonstrated unprecedented bit rates recently. 3 Gbit/s is demonstrated in [8]. A full duplex 10-Gbit/s, 60-GHz ROF orthogonal frequency-division multiplexing (OFDM) system over a 50-km single-mode fiber (SMF) and 4-m wireless transmission is demonstrated in [9]. 48-Gbit/s Fi-Wi systems are demonstrated in [10] over a 400-km fiber link using coherent ROF. Many other such impressive high-bit-rate systems have been reported recently.

1.1.2 ROF for Millimeter Wave Bands

Another pressing issue in wireless communication scenarios is the spectrum crunch. As the lower end of the spectrum becomes more crowded, there is ongoing effort to utilize the presently unused high-frequency spectrum, up to millimeter wave bands, for cellular wireless communications. For example, FCC allocated a 7-GHz spectrum for license-free operation between 57 and 64 GHz, which is sufficient for multi-Gbit wireless connections. Industry Canada has opened large blocks of spectrum in the 70/80/90-GHz range for wireless applications. In Japan, 71–76, 81–86, and 94.1–100 GHz is allocated for fixed and mobile communication services. An international survey conducted by ITU-R for telecommunications usage indicates that there is international interest in 60–61, 64–66, and 71–76/81–86-GHz bands for wireless communications.

Several GHz of bandwidth is available in the millimeter-wave bands. Hence, few Gbit/s connections are envisaged. However, the wireless channel has to be very short at these millimeter-wave frequencies for many reasons, in addition to those discussed earlier in the text. The first concern is the free-space propagation loss. According to the basic form of the well-known Frii equation, the free-space power loss of an electromagnetic wave is proportional to the square of its carrier frequency $f_c$:

$$\text{path loss} = \left(\frac{4\pi df_c}{c}\right)^\gamma$$

(1.1)

Here, $c$ is the speed of light, $\gamma$ is the path-loss exponent, and $d$ is the separation between the mobile unit and the base station antenna. Here, antenna gains are assumed to be unity. In free space, $\gamma = 2$. However, measurements have shown that the path-loss exponent can vary from 1.5 to 6 depending on the propagation environment. According to Frii’s formula in free space, the loss at 72 GHz will be $(72^2) = 5184$ times, or 37 dB higher than the loss at 1 GHz. If the path-loss exponent is high, say 4, this loss would be 74 dB higher. In addition, the millimeter-wave bands penetrate only a little through walls and are typically affected by rain and fog; a fading margin of 40 dB or above is required to overcome these effects.

A unique property, known as oxygen attenuation, is associated with 60-GHz signals. The oxygen attenuation is typically 12–16 dB/km (i.e., half of the energy is absorbed for every 200 m the signal travels), which is the main reason that 60-GHz links cannot cover the distances achieved by other millimeter-wave links.

ROF systems are ideal to support these millimeter-wave band wireless systems due to a number of reasons. Firstly, optical fiber is the best and probably the only medium for the transmission of millimeter-wave signals and to feed the access points. Secondly, microwave photonic
techniques can be deployed effectively in millimeter-wave bands to generate and process these millimeter-wave signals [11]. Impressive bit rates are demonstrated in many cases [9, 10].

1.1.3 Serving Special Areas

Providing satisfactory communication services in tunnels, underground subway networks, and mines has always been an issue. An increasing number of subway commuters now demand communication services and Internet access during their commute. Reliable communication has become a mandatory requirement for underground mines after the Mine Improvement and New Emergency Response (MINER) Act of 2006. Fi-Wi is a prominent candidate to provide wireless access to underground mines and tunnels. Leaky feeders or radiating cables are widely used in mines to radiate the RF signals. The leaky feeders, acting similarly to embedded linear antenna arrays, are often connected to the surface using ROF links.

ROF Fi-Wi is also an excellent solution to rapidly set up wireless networks for events where a mass gathering is expected, as witnessed by the Sydney Olympics example described above. ROF also played a significant role at London Olympic Park (and the associated underground tunnel system) in 2012. More similar successful deployments are expected because of the multitude of advantages associated with fiber optics.

Another successful application of ROF is in providing wireless access along highways and railway tracks. Optical fiber typically exists or can easily be laid in these areas. With the increased interest in vehicular area networks, Fi-Wi access points have much to contribute. There is a market need to provide communication services and Internet access to train commuters. These systems can also effectively use a Fi-Wi access network. In one such design effort, the train is configured as a ‘moving cell.’ This cell is given coverage from fixed ROF access points and handed over to the next access point as the train moves.

1.1.4 Value-Added Use for Existing Fiber

There is plenty of fiber already laid in major cities. This preinstalled fiber reaches many neighborhoods and buildings due to the widespread deployment of passive optical networks (PONs), high-speed digital subscriber loops (DSL), and hybrid fiber–coaxial (HFC) networks. Often, fiber is preinstalled along major infrastructure such as railway tracks, highways, and electric power cables for future use. When fiber cables are installed, they would typically have 2, 4, 6, 12, 24, 48, 96, 144, or 288 strands. Not all this fiber would normally be illuminated. Often there will be dark (unused) fiber in a conduit that can readily be used for Fi-Wi systems. Even if all the strands are used, it is more cost-effective to launch an additional wavelength with RF modulation to an existing fiber than laying new fiber. This possibility reduces the deployment cost as well as the lead time to implement Fi-Wi networks. Therefore, cable TV providers (who own large fiber-coaxial networks), Telco (DSL owners), city municipalities, and railway companies are becoming interested in using their existing fiber to provide wireless access for internal use or to make additional revenue.

The power grid is becoming smart and there is an increasing requirement to provide multiple levels of communication between various elements of the power grid. Wireless last mile is