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,
Radio over Fiber for Wireless Communications

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

---

1 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

Figure 1.1 Simple Fi-Wi access scheme with point-to-point fiber links
Radio over Fiber for Wireless Communications

Figure 1.2  Fi-Wi access scheme with a fiber bus network

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 $0.8 \times 1.8 \text{ km}^2$ 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 $f_c$:

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

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
Introduction

often involved. ROF is a potential candidate in this scenario as well. This will be a value-added service for the fiber, which has often been laid along with power lines.

1.1.5 Advancements in Microwave Photonics

Microwave photonics (MWP) enables the generation, transmission, and processing of microwave signals with unprecedented features compared with other electrical-domain approaches. An MWP signal processor brings supplementary advantages inherent to photonics, such as low loss, high bandwidth, and immunity to electromagnetic interference. MWP signal processing also provides features which are very difficult or even impossible to achieve with traditional technologies, such as fast tunability and reconfigurability.

There has been impressive progress in microwave photonics in recent times [12]. Novel photonic techniques have been devised and verified experimentally for the generation, amplification, frequency translation, and filtering of radio and microwave signals. These researchers use the Fi-Wi system as a hot test bed and report a multitude of novel techniques and exciting results. This creativity opens up new possibilities in Fi-Wi network architectures and functionalities.

Microwave photonics have opened up many new possibilities. Very stable and clean microwave signals can be optically generated by optical heterodyning or by optical frequency multiplying/dividing techniques. Radio signals can be amplified in-fiber using popular erbium-doped fiber amplifiers. Optical signal processing has many applications in wavelength-division multiplexing (WDM) ROF networks. Various optical filters (such as fiber Bragg gratings) are demonstrated to demultiplex wavelengths as well as RF subcarriers [13]. Radio waves can be up/down-converted (frequency translation) using optical nonlinearities. This enables low-frequency transmission over fiber and up-conversion at the RAP. The modulation depth can be adjusted using optical filters [14]. Single-sideband optical modulation, which has superior transmission properties over dispersive fiber, can be generated at the millimeter-wave scale using MWP techniques.

For example, Fig. 1.3 shows the magnitude spectrum inside the fiber of a subcarrier-multiplexed ROF link. Note that each subcarrier is separated from the main (optical) carrier

![Figure 1.3 Subcarrier-multiplexed ROF signal](image)
If $f_2 = 2.4 \text{ GHz}$, filter $BW < 38.6 \text{ pm}$.

**Important Parameters:**
1. Frequency separation $(f_j - f_i)$
2. Slope of the bandpass filter
3. Flatness of the filter top
4. Modulation depth

**Figure 1.4** Ultra-narrow microwave photonic filters can be used to demultiplex subcarrier-multiplexed RF signals.

**Figure 1.5** An empirical realization of an ultra-narrow microwave photonic notch filter using fiber Bragg gratings. Designed at Ryerson Communications Lab.

by its radio frequency $f_1$, $f_2$, respectively. In essence, this is a double-sideband spectrum. Fig. 1.4 shows conceptually how subcarrier-multiplexed RF signals can be optically demultiplexed (in-fiber) using specially designed ultra-narrow bandpass filters. Such a filter can be designed using special fiber Bragg gratings. The experimental transfer function of such a notch filter is shown in Fig. 1.5. This filter can be configured as a bandpass filter when used in a reflective arrangement with an optical circulator. This arrangement can extract a double-sideband (DSB)-modulated RF signal at frequency $<2.2 \text{ GHz}$ from other...
Introduction

Centrals

The ROF Link

Photodiode

LNA

RA

P

2.5 GHz

1.8 GHz

2.5 GHz

1.8 GHz

Figure 1.6 An all optical demultiplexing Fi-Wi network arrangement

high-frequency subcarriers, as shown in Fig. 1.4. This kind of all optical demultiplexer can be very useful in arrangements like Fig. 1.6.

1.1.6 Transparent System Enhancement

It is important to understand that Fi-Wi is not a new wireless standard or a new wireless system. Rather, it is an enhancement in the access network infrastructure that can be applied to almost all existing and future wireless systems. It enables rapid installment of a distributed antenna scheme. It splits the high-cost base station into a central processing unit and spatially distributed multiple radio access points.

If the ROF link is properly designed, the portable device should be unaware of the existence of fiber in its radio path. Explaining the design of such Fi-Wi systems is the objective of this book.

Ideally, the Fi-Wi extension should have the capability to support various current and future wireless standards, independent of wireless system specifics, as long as the carrier frequency falls within the passband of the ROF link. For example, the same ROF links should be able to transmit either time-division multiple access (TDMA), core-division multiple access (CDMA), or OFDMA radio signals without modification as long as their carrier frequencies are the same (or close). Properly designed, the ROF link can also carry multiple RF carriers simultaneously in a subcarrier-multiplexing manner and support multistandard radio as demonstrated at the Sydney Olympics.

1.2 Basic Fi-Wi System Architecture

This section describes a general, very basic ROF Fi-Wi system architecture. Here we consider the scenario in which each RAP is connected to the CBS with a point-to-point fiber-optic link as shown in Fig. 1.1. In reality, instead of the simple point-to-point architecture shown in the figure, fiber networks can be used to interconnect multiple antenna points using less fiber in a cost-effective manner (Fig. 1.2).
1.2.1 Two Types of Modulation

It is very important to notice that there are two entirely different forms of modulation/demodulation processes involved in ROF systems. These are clearly defined below to avoid confusion. They can be better understood by looking at Figures 1.7 and 1.8.
Introduction

**Baseband-RF modulation.** We refer to the legacy modulation process in wireless networks, i.e. RF carrier modulation by the baseband information sequence at the central base station, as ‘baseband-RF modulation.’ The corresponding demodulation at the portable unit is referred to as ‘RF-baseband demodulation’. The modulation technique will be based on the requirements of a given wireless network. (For example, it would be GMSK if the network is GSM or it could be QPSK or QAM if the network is LTE or WiMAX.) A Fi-Wi design engineer will usually have no control over the kind of baseband-RF modulation. It is better to leave this modulation unaltered due to fiber insertion.

**RF-optical modulation.** Modulating the optical carrier with the RF signal at the laser or in an appropriate external modulator is referred to as ‘RF-optical modulation.’ The corresponding demodulation at the optical receiver is referred to as ‘optical-RF demodulation.’ The Fi-Wi system engineer can decide this modulation type and characteristics to better suit the design requirements.

Let us first consider the downlink of a Fi-Wi link. The baseband-RF modulation is done at the base station as usual. This radio signal then modulates the optical carrier at the optical transmitter (RF-optical modulation). This is often done using intensity modulation, which is the most common technique. Direct detection of the light energy is done at the photodetector in this case. Together it is called the IM/DD technique. Coherent RF-optical modulation is also possible, which will provide a better solution at the expense of high complexity. In coherent RF-optical modulation, both the phase and the amplitude of the light wave are modulated by an RF signal. Hence, the phase of the optical carrier needs to be tracked at the fiber-optic receiver, which will require very stable, narrow line width optical sources and phase-locked photonic receivers.

The RF-modulated light wave then travels to the remote RAP. At the RAP, the RF signal is extracted from the optical carrier using an appropriate photodetector and bandpass circuitry. This RF signal is then amplified and relayed to the portable units via the wireless channel. In the uplink direction, the reverse operations are performed; first the RF signal goes through the wireless channel, and then it travels via the fiber-optic link.

Simply said, in an ROF Fi-Wi system, the fiber-optic link is inserted between the remote antenna and the CBS. In a well-designed Fi-Wi system, the end user had better be unaware of the presence of the fiber link. This means that no modifications need to be carried out on the handset, which will also ensure the same handset can be used in the legacy wireless network as well as in a Fi-Wi network, enabling seamless roaming between these two networks.

Since the number of RAPs will be large, they should typically be cost-effective, small, robust, and of low complexity. To meet these requirements, the number of functions performed by an RAP should be minimal. For example, there should be no up/down-conversion or digital signal processing at the RAP. This is the advantage of transmitting RF versus intermediate frequency (IF) or baseband signal over fiber.

In Fig. 1.1 it is seen that the RAP must consist of at least one O/E (optical-to-electrical converter), E/O (electrical-to-optical converter), and a radio antenna. In the downlink direction, RF amplifiers need to be incorporated to amplify the signal to a level suitable for radio transmission. In the uplink direction, automatic gain controllers may be incorporated to compensate for the fluctuations in the RF signal level. While the RAP should be designed to function at the passband for the carrier frequency of the wireless system(s) to be supported, it is good to make the RAP independent of the radio signal formats (such as CDMA or OFDM), so that it can support different wireless services without modification. The power consumption and maintenance requirements of the RAPs should of course be low.
1.3 Major Issues

In the design of a Fi-Wi system an engineer will mainly be faced with the following design issues, which we have covered in detail in this book.

**Limited power budget.** Although the fiber-optic link has huge bandwidth, the optical fiber and the modulator can handle only a limited amount of RF power for various reasons as described in Chapter 3. In addition, power loss will be incurred due to optical-to-electrical and electrical-to-optical conversion. The RF signal will be attenuated along the length of the fiber. Therefore, only a limited RF power will be received at the RAP. Amplification at the RAP will help only to a certain extent, for reasons explained later. Therefore, there will be an inherent limitation on the radio cell size, depending on the fiber length and RF bandwidth. These and many other system parameters have interesting interrelationships.

**Cumulating noise.** Of the optical noise powers, mainly the quantum noise, the relative intensity noise, and the thermal noise will be added to the RF signal in the optical link. In addition, wireless channel noise and various interferences will be added at the air interface. Owing to the analog nature of the system, the noise powers added in both the optical and wireless channels will cumulate and result in a poor signal-to-noise ratio (SNR) eventually. These noise powers also show interesting dependencies on various parameters, like the RF signal bandwidth, radio cell size, and fiber length.

**Distortion in the Fi-Wi link.** The optical modulators, both laser and external, are inherently nonlinear devices. The nonlinear distortion is a major concern in ROF links, since they are analog and will have large variations in the RF signal power. The ROF links are concatenated with the time-varying dispersive wireless channel, which will further deteriorate the signal quality. The design engineer is left with the challenge of designing distortion-compensation schemes for the concatenated Fi-Wi channel, which is not easy. A major portion of this book is devoted to developing signal-processing algorithms for the estimation and equalization of the concatenated Fi-Wi channel.

1.4 Other Fiber-Feeder Approaches

1.4.1 Digitized ROF

Since nonlinear distortions, limited dynamic range, and cumulating noise are major concerns with the analog ROF backbone, alternative approaches are also investigated by researchers. One approach is to transmit a digitized RF signal over fiber from the base station to the radio access point. The falling cost of high-speed D/A and A/D converters has led to heightened recent interest in digitized radio over fiber links (DROF). Note that in DROF, the I and Q baseband digital signals immediately after the digital signal processor are converted to optical and transported via the fiber. This means that the remote radio heads can be relatively simple too, consisting of D/A converters, up-converters, and amplifiers in the downlink direction and A/D converters, down-converters, and amplifiers in the uplink direction [15]. Signal processing and modulation functions will take place in the CBS. Therefore, this architecture also satisfies the requirement that the RAP remains small and relatively simple. In fact, such digital links have been specified for current wireless systems (UMTS, WiMAX, and LTE) to connect digital base stations to remote radio heads [7].
Introduction

When the central base station has to be connected to multiple remote units, often some kind of multiplexing is required to reduce the amount of fiber used. A combination of wavelength and subcarrier multiplexing is the most convenient method in analog ROF links. In digitized ROF links, this is often done via time-division multiplexing (TDM) with a combination of WDM if necessary.

1.4.2 Intermediate Frequency over Fiber

Another approach is to transmit a lower, IF signal over fiber rather than the RF signal. IF transmission has a few advantages:

- It will better handle fiber dispersion issues. In some cases, multi-mode fibers can be deployed.
- It allows the use of low-frequency, low-cost components, especially the modulator and demodulator.
- It allows the use of a simple intensity modulation/direct detection transmission scheme and direct modulation of semiconductor laser diodes.
- It allows multiple channels to be transmitted over a single link at the same radio carrier frequency, for example, to carry multiple MIMO channels.

These advantages make IF transmission a good choice for situations where the radio carrier frequency is higher than approximately 3 GHz or where several radio channels must be transported simultaneously over a single link. However, this approach will require frequency translation at the CBS and RAP. Sometimes a low-frequency reference tone may need to be transported over the ROF link to ensure precise frequency locking.

1.5 Book Outline

In Chapter 2, the basic elements of Fi-Wi channels are discussed. This includes: (1) directly and externally modulated optical transmitters, namely, laser diodes and Mach-Zehnder modulators; (2) the fiber channel (multi-mode or single-mode), including different dispersion mechanisms and their effect on RF transmission; (3) the PIN and APD receivers and their noise/gain characteristics; and (4) the wireless channel basics, including different propagation models.

Power budget calculations taking into account the cumulating SNR is crucial for Fi-Wi system design. There are two analog channels cascaded in Fi-Wi systems. The signal is weak at both the optical and wireless receivers. Different noise powers are added at both these receivers. Therefore, two SNRs can be defined, one for the electrical domain and the other for the optical domain. The result is a weighted sum of these two SNRs, smaller than the smallest of these two. There is a large loss (typically 20 dB) due to E/O and O/E conversion, which will have a negative impact on the overall power budget. To make things worse, the optical domain loss appears twice in the electrical domain. These issues pose an inherent inverse relationship between the optical and wireless channel lengths. These issues are analyzed in Chapter 3.

The relative intensity noise (RIN) of an ROF link is supposed to be constant provided the mean optical power does not change. However, on many occasions it has been observed that the RIN increases with the modulating RF signal power as well. This ‘dynamic RIN’ poses
an additional challenge and has the effect of saturating the SNR. Chapter 4 mathematically derives a new expression for this dynamic RIN in a deeply modulated system. This expression reduces to the traditional expression when the modulation index is small.

Chapters 5 and 6 describe issues with multisystem Fi-Wi links that use subcarrier-multiplexed ROF links. Although the fiber has enough bandwidth, the design of SCM ROF links is not straightforward. Superposition does not hold, due to nonlinearity. The nonlinear distortion in each RF signal depends on the total RF power that affects the weaker signal adversely. There will be cross-talk between two wireless systems in addition to in-band nonlinear distortions. In these chapters, two conceptually different wireless systems (one cellular radio and one ethernet wireless LAN system) are considered for the transportation via a Fi-Wi link. When signals belonging to these two wireless systems are simultaneously transmitted over the Fi-Wi channel, both physical and MAC layer analysis is required to get an insight into the performance. Closed-form expressions for the cumulative SNRs of both systems are derived in these chapters considering noise, nonlinear distortion, and multiuser interference.

Externally modulated ROF links provide much higher bandwidth and flexibility, and support higher transmission power. However, finding an optimum bias point is important due to the nonlinear nature of the Mach-Zhender modulator. In chapter 7, it is shown that how an optimum point can be obtained that would improve the RF link gain, maximize the dynamic range while minimizing the noise figure. The expression for the harmonics of the Mach–Zehnder modulator when more than one subcarrier is transmitted is also given by the expansion of the Bessel functions.

Chapter 8 describes the fundamental principles behind the adaptive baseband nonlinear modeling of Fi-Wi systems. Although various attempts in the photonic and microwave domains in the past show improvement, the nonlinearity is better dealt with at baseband using a digital signal processing approach. In addition, baseband DSP approaches enable adaptive algorithms and are compatible with many other wireless network algorithms. Note that although the nonlinear distortion happens in the optical domain, it will eventually be reflected in the information-bearing baseband symbols. Therefore, dealing with the distortion directly at baseband is more fruitful.

Once the nonlinear Fi-Wi system is modeled, suitable compensation algorithms can be developed. This is done considering an AWGN wireless channel in Chapter 9. This chapter also shows how amplitude and phase nonlinearities can be compensated individually by real-valued adaptive filters. The chapter introduces an asymmetric architecture where compensation for both the forward link and reverse links is done in the central base station, leaving the mobile unit without any modification.

At high bit rates, multipath dispersion and intersymbol interference (ISI) issues of Fi-Wi systems become important. This ISI is combined with the nonlinear distortion in a Fi-Wi link. Since the fiber and wireless channels are concatenated, the combined channel has to be estimated jointly. This is a unique challenge. Chapter 10 shows how this estimation can be done. Following the estimation, a joint compensation scheme that handles both the linear dispersive dynamic wireless channel and the static nonlinear optical link should be developed. This is described in Chapter 11. The performance of the equalizer is analyzed in Chapter 12.

Fourth and fifth generation wireless networks consider CDMA, OFDM, or a combination of these two. Among these, the multiuser CDMA Fi-Wi approach provides a unique challenge. Here, multiple users will share the same ROF link. Hence, they will have a common static
nonlinear channel in series with individual dynamic wireless channels. This issue is dealt with in Chapter 13.

Chapter 14 provides a brief history on wireless communications and outlines possible future directions. The major aspects of 4G systems and expectations of 5G systems are discussed. It is also shown how fiber feeders will play a vital role in future wireless systems. OFDM wireless systems are described and the benefits of combined OFDM–CDMA systems are discussed. Various attempts to reduce the well-known ‘peak to average power ratio’ issue are reviewed. An adaptive modulation scheme to reduce OFDM Fi-Wi system impairments is explained.