Fiber-Wireless Solution for Broadband Multimedia Access

by Stephen Z. Pinter and Xavier N. Fernando
Ryerson University, Toronto, ON

Abstract

The increasing demand for high-capacity multimedia services in real-time demands wireless broadband access. In order to meet this demand, a fiber based wireless access scheme using radio-over-fiber (ROF) technology can be used and is discussed in this article. Fiber based wireless (Fi-Wi) access schemes effectively combine the high capacity of optical fiber with the flexibility of wireless networks. This approach enables rapid deployment of micro cells in cellular radio networks for capacity enhancement. Furthermore, a single sub-carrier multiplexed ROF link can support wireless LAN, cellular radio, and CATV services simultaneously. ROF technology can also transmit millimeter radio waves to the surrounding neighborhood for LMCS type systems. The focus of our research group ADROIT is to investigate various issues in this scenario such that ROF becomes a feasible technology to provide a cost-effective, high performance solution for broadband access. We have devised a system identification technique for a concatenated fiber-wireless channel, and have proposed various compensation schemes to equalize the time varying linear wireless plus static nonlinear optical channel. Another of our projects focuses on supporting both cellular CDMA and IEEE 802.11 signals over the fiber-wireless channel. We have also performed various experimental studies on the ROF approach and have been working with optical and electrical signal processing for performance improvement. This article provides an overview of ADROIT research and presents some noteworthy results.

Sommaire

La demande croissante pour des services multimedia temps réel de haute capacité exige un accès sans fil à large bande. Pour répondre à cette demande, un procédé d'accès sans fil sur fibre optique utilisant la technologie radio-sur-fibre (RSF) peut être utilisé et sera discuté dans cet article. Les procédés d'accès sans fil basés sur fibre (Fi-Wi) combinent la haute capacité de la fibre optique à la flexibilité des réseaux sans fil. Cette approche permet le déploiement rapide de micro-cellules dans les réseaux cellulaires pour l'accroissement de capacité. De plus, un simple lien RSF sous-porteur multiplexé peut supporter des services de réseau local sans fil, radio cellulaire, et câblodistribution simultanément. La technologie RSF peut aussi transmettre des ondes radio millimétriques pour des systèmes de télécommunications multipoints locaux. La cible principale de notre groupe de recherche ADROIT est l'investigation de divers sujets dans ces scénarios de façon à ce que la RSF devienne une technologie pouvant fournir une solution à haute performance et rentable pour l'accès à large bande. Nous avons conçu une technique d'identification de systèmes pour un canal fibre-sans-fil concaténé, et avons proposé plusieurs procédés de compensation pour égaliser le canal optique en variance temporelle linéaire sans fil et nonlinénaire statique. Un autre de nos projets se penche sur le support de signaux AMRC (CDMA) et IEEE 802.11 sur canaux fibre-sans-fil. Nous avons aussi réalisé plusieurs études expérimentales sur l'approche RSF et avons travaillé avec du traitement de signal optique et électrique pour accroître la performance. Cet article fournit un exposé des recherches de l'ADROIT et présente certains résultats significatifs.

1.0 Introduction

Over the past decade there has been substantial progress in the areas of wireless and optical communications. The driving force behind this advancement has been the growing demand for multimedia services, and hence broadband access. Present consumers are no longer interested in the underlying technology; they simply need reliable and cost effective communication systems that can support anytime, anywhere, any media they want. As a result, broadband radio links will become more prevalent in today's communication systems.

Furthermore, new wireless subscribers are signing up at an increasing rate demanding more capacity while the radio spectrum is limited. To satisfy this increasing demand, the high capacity of optical networks should be integrated with the flexibility of radio networks. The Advanced Radio-Optics Integrated Technology Research Group (ADROIT) at Ryerson University concentrates on this integration; this leads us to the discussion on the fiber-based wireless access scheme using radio-over-fiber (ROF) technology. ROF refers to a fiber optic link where the optical signal is modulated at radio frequencies (RF) and transmitted via the optical fiber to the receiving end. At the receiving end, the RF signal is demodulated and transmitted to the corresponding wireless user. By implementing the above technique, ROF technology is able to alleviate the increasing demand for high-bandwidth services through the implementation of micro/pico cellular architectures. The primary focus of the ADROIT research group is to investigate (optical and electrical) signal processing strategies that can provide a cost-effective, high performance solution for high-speed fiber based wireless access.

2.0 Radio-Over-Fiber for Fi-Wi Systems

The fiber-wireless solution for cellular networks is shown in Figure 1 (the fiber-wireless downlink). This solution increases the frequency reuse and enables broadband access by providing a micro/pico cell scenario for cellular radio networks. The mirco/pico cell scenario is possible through the use of radio access points-RAP in Figure 1. These inexpensive low power RAPs provide wireless access instead of conventional base stations. It is important to keep the RAPs complexity and cost at a minimum in order to allow for large scale deployment. By doing so, a large cell can easily be split into smaller cells by dispersing RAPs throughout. These robust RAPs are connected to the central base station via the ROF links.

2.1 The Radio-Over-Fiber Technology

In any RF communication system, the baseband information is modulated to a suitable carrier frequency. Both the modulation scheme and the carrier frequency are predetermined (Figure 2). For example, QPSK (with CDMA) is used at 900 MHz in IS-95 cellular radio system and OFDM at 2.4 GHz is used in IEEE 802.11 wireless LAN. The purpose of the ROF link is to provide a transparent, low distortion communication channel for the radio signal for antenna remoting.

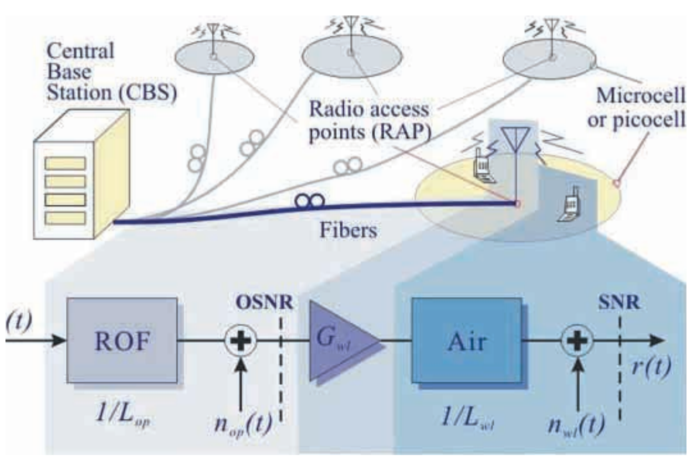

Figure 1: ADROIT fiber-wireless solution for cellular radio networks

Laser diodes can be directly modulated up to several GHz of radio fre-

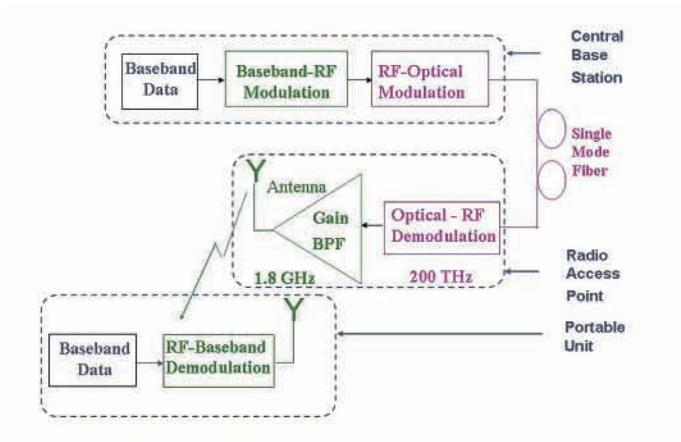

Figure 2: Two types of modulation involved with the radio-over-fiber approach

quency depending on their resonance frequency. Up to several GHz directly modulated ROF transceivers are commercially available. At higher frequencies, external modulators such as the Mach-Zehnder interferometer should be used.

ROF transmission offers many advantages in wireless systems, some of which are:

- Huge bandwidth that enables multiplexing several radio channels; each radio channel may belong to a different system such as wireless LAN and cellular radio,
- Ability to use existing dark/dim fibers to transmit the radio signal (dim fiber can be used with WDM techniques),
- Inherent immunity to electromagnetic interference, and
- Allowing for transparent operation because the RF to optical modulation is typically independent of the baseband to RF modulation.

ROF also allows for easy integration and upgrades since the electrical to optical conversion is independent of baseband to RF modulation format. Conventional transmission mediums such as copper coaxial may not be completely replaced by optical fiber, but in applications where factors such as RF power loss, future system upgrades and transparency are considered, fiber is regarded as the most practical and efficient medium. Even though the prospects of ROF are substantial, there is still plenty of research to be carried out in this area before widespread deployment can be considered.

Table 1: Myths and realities of fiber-wireless access

The Myth	The Reality
Optical fiber is mostly useful to transmit digital (SONET) type data carrying voice (telephony) signals.	Not true. Optical fiber is an excellent wideband channel and any broadband (analog or digital) signal can be transmitted via fiber with very low distortion. Analog transmission has been widely used in CATV systems.
Optical access networks means running fiber to every house (fiber-to-the-home, FTTH). This is too expensive and will not materialize in the near future.	Not necessarily. There is plenty of dark (unused) and dim (partly used) fiber running in our neighborhood in most major cities. These existing fibers can dramatically enhance the access network capacity with the Fi-Wi approach.
Optical and wireless networks are independent.	Access networks can be effective combinations of both optical and wireless techniques. This combination supports mobility as well as broadband access.
Optical fiber may be useful to transmit millimeter waves which otherwise can't be transmitted cost effectively.	Even at 900 MHz, 1800 MHz and 2400 MHz frequencies radio-over-fiber technology is cost effective; see the Sydney Olympics example below.
Only few isolated researchers work in this area.	There are commercial products available for Fi-Wi networks and even books have been written on the technology [3]. Also see the Sydney Olympics example below.

2.2 Supporting Multiple Wireless Standards

Studying the effects of transmitting multiple wireless standards over a single ROF link can be very beneficial. Today, 3G wireless technologies have a bit rate of more than 2 Mbps and wireless local area network (WLAN) technologies can provide a bit rate as high as 54 Mbps with IEEE 802.11. The integration of these two technologies can increase the bit rate available for applications, while maintaining reasonable mobility for end users.

Some work in this area has been done in [1] where the transmission of multiple wireless standards over an ROF network is investigated; however, the knowledge in this area is still limited. Currently, we concentrate on the different issues of supporting both cellular CDMA and IEEE 802.11 type Wi-Fi signals over the fiber-wireless system. This can be done either in a sub-carrier multiplexed [2] or baseband plus ROF manner. Although the fiber has several GHz of bandwidth, the cross coupling due to nonlinearity impairs system performance and our focus is to quantify it and to find feasible solutions.

2.3 Issues with the Fi-Wi System

Several observations can be made from Figure 1. First, signal processing should not be done at the RAP for cost considerations. Therefore, compensation should be done at the portable unit or at the central base station. By performing most of the signal processing at the central base station, i.e. by asymmetric distribution of the complexity, the cost can be shared by many users and therefore helps reduce overall system cost. Second, the compensation of the concatenated fiber-wireless channel should be handled jointly. This is a challenging task because of the time varying multipath wireless channel in series with the nonlinear optical channel. Furthermore, the uplink and downlink require different solutions. Third, it is desirable not to modify the portable units because of the ROF link. In other words, the portable unit should not be aware of the existence of the ROF link. This makes seamless roaming between fiber-based and conventional wireless systems possible.

One of the major issues with ROF is the nonlinear distortion of the optical link. This is due mainly to the laser diode (and partly to the high-gain RF amplifier at the optical receiver), and is most dominant in a multiuser environment. Several approaches have been proposed to characterize and solve the problem of nonlinear distortion. In [4], the authors demonstrated how external light injection into a directly modulated laser diode can be used to enhance the linear performance of a multi-channel ROF system operating at a frequency of 6 GHz. In [5], low-cost predistortion circuits able to compensate second- and third-order laser distortions in multiservice ROF industrial systems were developed. Another approach mitigated the nonlinear distortion in the network layer [6].

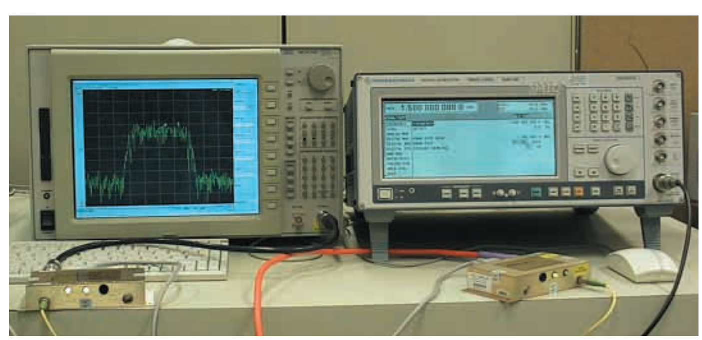

Figure 3: ROF experimental setup. In this photo, a Rohde & Schwarz signal generator sends a WCDMA RF signal through the ROF link and into the Tektronix WCA380 wireless communication analyzer

3.0 ADROIT Solutions for the Issues

3.1 Nonlinearity Compensation

An adaptive baseband model for the ROF link was developed and two different predistortion schemes for the nonlinearity were proposed; one is currently being implemented in an FPGA platform. With the first scheme, the predistortion is done using a look-up table. In the second scheme, higher order adaptive filters are trained to inverse model the ROF link. With both of these approaches, simulation results show good performance improvement, but sometimes requiring a power back off.

Asymmetric compensation is a scheme that allows for most of the signal processing to be done at the central base station. This is achieved by doing predistortion for the downlink and post compensation for the uplink [7]. The issues associated with this asymmetric arrangement are discussed in detail and a unified analysis carried out in [7].

3.2 Estimation and Equalization

Even though ROF provides an excellent broadband link allowing for the communication of several channels, the wireless channel introduces inter symbol interference (ISI) at high bit rates. Along with the nonlinearity, available linear dynamic range becomes a major concern, especially in the uplink. A large linear dynamic range is required in the uplink, where the received signal first travels through the wireless channel (resulting in path losses, fading and shadowing) before entering the optical fiber. Several researchers (for example [8]) address the issue where rapidly fading dispersive linear channels are estimated and equalized. However, in the Fi-Wi system, the ISI is coupled with the nonlinear distortion of the optical link, thereby demanding nonlinear channel estimation and equalization techniques.

3.2.1 Estimation

In order to limit the effect of nonlinear and ISI distortions, estimation, and subsequently equalization, of the concatenated fiber-wireless system should be done. Estimation of the concatenated fiber-wireless channel is an important step towards equalization of the linear channel and linearization of the nonlinear channel. In our estimation algorithms we always consider both wireless channel noise and optical channel noise (quantum, thermal and relative intensity) which are shown in Figure 1 as $n_{wl}(t)$ and $n_{op}(t)$, respectively.

A complete identification of the ROF uplink has been performed in [9] for a single user environment. Expanding identification to a multiuser environment is currently being studied; simulations yield promising results. The wireless channel was identified using correlation analysis, and the nonlinear link was identified using a least squares polynomial fit. It should be noted that our identification was performed using multiple maximal-length pseudonoise (PN) sequences. This is a major advantage because multiple PN sequences are already widely used in spread spectrum communications.

3.2.2 Equalization

Once the channel is estimated, an appropriate equalizer must be devised for the compensation of the linear and nonlinear parts. The fiber-wireless uplink is a Wiener system and therefore a Hammerstein type decision feedback equalizer (DEF) was developed to compensate for it. This equalizer compensates for the linear and nonlinear distortions separately. This modular architecture is attractive for commercial implementation. The receiver consists of a polynomial filter, which inverse models the optical link, and a linear DFE arrangement that compensates for the wireless channel dispersion. The DFE filter parameters were optimized and performance analysis was carried out.The Hammerstein type equalizer discussed above was implemented for a single user. Currently, ADROIT is working on expanding equalization to a multiuser environment.

3.3 Noise Characterization and Cancellation

From Figure 1 it is observed that there are two signal to noise ratios involved in the fiber-wireless system. The optical noise (n_{op}) will be dominant if the fiber is too long and the wireless channel noise (n_{wl}) will be dominant if the radio cell is too large. The cumulative SNR will be smaller than the smallest SNR. This issue is discussed in detail in [10]. The optical SNR deteriorates with wideband RF signals; this becomes an issue in emerging 4G systems that opt for WCDMA type wideband RF signals. ADROIT has also been working on improving the SNR performance of the Fi-Wi system.

Relative intensity noise (RIN) plays an important role in analog fiber optic links. This is especially true with ROF applications because the SNR at the remote antenna end is critical for system performance. Conventionally, the RIN is taken to be proportional to the square of the mean optical power; however, it has been shown that RIN also depends on the modulation index. An improved mathematical expression for the dynamic RIN was derived from fundamental principles and as a function of the modulation index as well. This is a fundamental contribution and will most likely change the way ROF links are analyzed.

4.0 Some Numerical Results

The research results presented herein discuss the BER performance of the ROF link under various conditions[1].

Figure 4 shows the relationship between average BER and fiber length when the RF bandwidth is 5 MHz (WCDMA) and 1.25 MHz (IS-95). A single active user is considered and the radio cell radius is 2.5 km. It can be seen that for both cases as the fiber length increases, the average BER gradually increases as well. This is expected because, as the fiber length increases, signal attenuation in the fiber increases and this decreases the SNR in the ROF link. This phenomenon gives slightly different results depending on the RF bandwidth. For example, with 5 MHz RF bandwidth, the noise collected in the ROF link is high because of the high noise bandwidth. However, WCDMA has larger spreading gain and generally it will give a low BER compared to an IS-95 signal.

In Figure 4, because of the above contradicting issues, there is a crossover of the two curves that happens at a fiber length of approximately 10 km. This occurs because at short fiber lengths the spreading gain dictates the BER and therefore the WCDMA signal with bandwidth 5 MHz performs better. At the other end, when the fiber length is longer, the limiting factor is the optical signal to noise ratio. In this case, the 5 MHz system performs worse because it collects more optical noise (nop).

The relationship between average BER and the radio cell radius for 1, 2, 5 and 10 users is shown in Figure 5. In this simulation the fiber length was fixed at 5 km. Overall, as expected, the average BER increases with radio cell radius and added users. At larger radio cell radii, the average BER is less dependant on the number of users, however, at small radio cell radii, the spread between the average BER for 1 user and 10 users is fairly large. The BER floor depends on the fiber length and optical-electrical conversion losses.

5.0 Conclusions

The projected impact of implementing ROF schemes is substantial. The deployment of optical fiber technology in wireless networks provides great potential for increasing the capacity and QoS without largely occupying additional radio spectrum. From the aforementioned benefits it is obvious that ROF technology will become ubiquitous in today's communication industry. The research performed by ADROIT will definitely help to provide a cost-effective, high performance solution for present and future high-speed fiber based wireless access systems.

6.0 Acknowledgement

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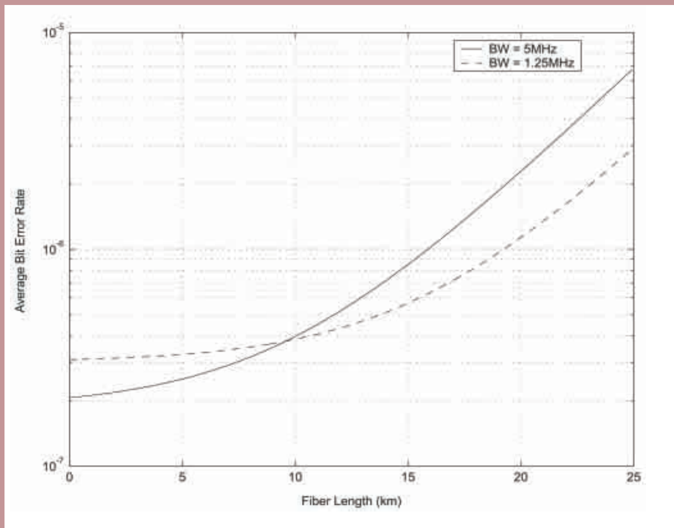

Figure 4: Average BER performance with fiber length.

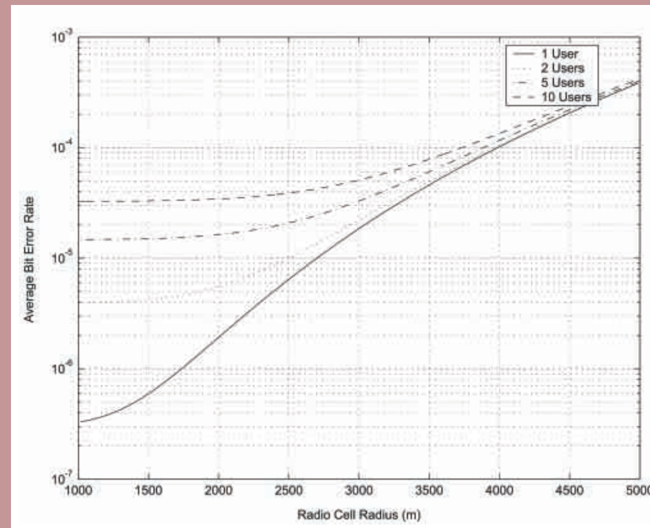

Figure 5: Average BER performance with radio cell radius.

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Application Example - Sydney Olympics

The BriteCell^{TM} fiber optic-based mobile communication system designed by Tekmar Sistemi was installed for the Sydney 2000 Olympics in order to handle the massive wireless traffic (especially at the opening and closing ceremonies).

On the opening day of the Olympics, over 500,000 wireless calls were made from Olympic Park venues. In the minutes leading up to the opening ceremony, over 175,000 calls were made by the 110,000 spectators in the sold out stadium.

Some vital features of the BriteCell^{TM} ROF system installation were:

1. Support for dynamic allocation of network capacity.
2. Support for 3 GSM operators.
3. Support for both 900 MHz and 1800 MHz cellular networks.
4. More than 500 remote antenna units (RAPs) were deployed.
5. Multiple layers of wireless in-building and external pico cell coverage systems were installed.
6. System was able to support the equivalent of 75% of Sydney's average central business district traffic.

Source: Fiber Optics Business, Nov. 2000.

About the authors

Stephen Z. Pinter received the B.Eng. degree (Hons.) in electrical engineering from Ryerson University, Toronto, in 2003 and is currently working towards the M.A.Sc. degree from the same university. His Masters thesis research is involved with estimation and equalization strategies for radio-over-fiber communication systems. More specifically, he is applying the Wiener/Hammerstein class of nonlinear systems to the radio-over-fiber environment. His current research interests include fiber-wireless access, channel estimation and equalization, and EDFA dynamics and gain flattening. He is an IEEE student member and can be reached at spinter@ieee.org.

Xavier N. Fernando obtained the B.Sc.Eng. degree (1st class Hons) from Peradeniya University, Sri Lanka. He got a Masters degree from the Asian Institute of Technology, Bangkok, and Ph.D. from the University of Calgary, in affiliation with TRLabs. He worked for AT&T for three years as an R&D Engineer. Currently he is an Asst. Professor at Ryerson University, Toronto. His research focuses on signal processing for cost-effective broadband multimedia delivery via optical wireless networks. He is a senior member of the IEEE, member of SPIE, Chair of the IEEE Communications Society Toronto Chapter and licensed Professional Engineer in Ontario, Canada. He can be reached at www.ee.ryerson.ca/~fernando.