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Radio over Fiber Technology for the Next Generation
Hamed Al-Raweshidy

4.1 Introduction

Chapters 1 and 2 have presented the main elements of the optical devices and the parameters related to radio over fiber: laser diode performance, intermodulation, RIN, and clipping noise. This chapter discusses in more detail the system performance of radio over fiber on Universal Mobile Telecommunication System/wideband code-division multiple access (UMTS/WCDMA). We start with an introduction to UMTS and WCDMA with an overview of radio over fiber technology for the UMTS system. The advantages and disadvantages of radio over fiber technology for third-generation (3G) and fourth-generation (4G) systems are also discussed. In addition, a simulation for both radio and optical systems is presented. Furthermore, an analytical model for evaluating the performance of WCDMA-based radio over fiber systems with numerical results showed an improvement in performance when the effect of voice activity monitoring on intermodulation distortion and clipping noise was taken into account.

4.2 Radio over Fiber Systems

Recently, optical fiber microcellular systems, in which microcells in a wide area are connected by optical fibers and radio signals are transmitted over
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an optical fiber link among base stations and control stations, has attracted much attention [1]. This is because of the low loss and enormous bandwidth of optical fiber, the increasing demand for capacity/coverage, and the benefits it offers in terms of low-cost base station deployment in microcellular systems, all of which make it an ideal candidate for realizing microcellular networks [1, 2]. In such a system, each microcell radio port would consist of a simple and compact optoelectronic repeater connected by an RF fiber optic link to centralized radio and control equipment, possibly located at a preexisting macrocell site.

Use of RF antenna remoting allows changes to the system frequency plan or modulation format to be done at a central location, without the need to modify any radio port equipment. Antenna remoting should also simplify the provision of system features such as rapid handover, dynamic channel assignment, and diversity combining.

This system will make extensive use of microcells and picocells in order to deliver high bandwidth. Such microcell systems can solve the frequency limitation problem because a number of base stations can be installed, the zone radius can be reduced, and the radio frequencies can be reused effectively in many radio zones [3]. The much lower power level eliminates the need for the expensive frequency multiplexes or high-power amplifiers currently employed at base stations. The limited coverage due to low antenna height greatly reduces the cochannel interference from other cells [4]. Radio over fiber (RoF) systems are now being used extensively for enhanced cellular coverage inside buildings such as offices, shopping malls, and airport terminals [1, 2, 5].

The WCDMA air interface can now be regarded as a mature technology that is ready to provide the basis for the third-generation wireless personal communication system known as the UMTS [3, 6]. These systems will make extensive use of microcells and picocells in order to deliver high-bandwidth services to customers. The benefit of using RoF for WCDMA distributed antenna systems is expected to be even more important, partly because of their higher frequency and bandwidth requirements [1, 2].

Two key features are expected to be employed in the UMTS system to minimize multiple-user interference: adaptive antenna arrays and fast closed-loop forward and reverse power control techniques [7; see also http://www.3gpp.org]. Other important techniques that are used to reduce multiple-user interference are cell sectorization and voice activity monitoring, particularly in speech-oriented cellular systems [8, 9].

The UMTS is designed to support simultaneous transmission of multiple services and data rates including video. One of the major drawbacks
in RoF systems is laser diode nonlinearity, which gives rise to intermodulation distortion and clipping noise. It is well known that intermodulation distortion and clipping noise are signal level dependent [10]. We envisage that in WCDMA RoF systems, voice activity monitoring will have an impact not only on multiple-user interference, but also on intermodulation distortion and clipping noise power. A full analysis for intermodulation distortion was given in Chapters 1 and 2, and Chapter 3 provides details of the dynamic range of microcellular systems.

4.3 Cellular Architecture

Increases in demand and the poor quality of existing service led mobile service providers to research ways to improve the quality of service and to support more users in their systems. In modern cellular telephony, rural and urban regions are divided into areas according to specific provisioning guidelines. Deployment parameters, such as amount of cell splitting and cell sizes, are determined by engineers experienced in cellular system architecture.

4.3.1 Cell

A cell is the basic geographic unit of a cellular system. The term cellular comes from the honeycomb shape of the areas into which a coverage region is divided. Cells are base stations transmitting over small geographic areas that are represented as hexagons. Each cell size varies depending on the landscape. Because of constraints imposed by natural terrain and man-made structures, the true shape of cells is not a perfect hexagon. Based on the radius of the cells, there are three types of cellular networks: macrocells, microcells, and picocells.

4.3.2 Macrocellular

A macrocellular network is deployed using relatively large cells with a diameter of 16 to 48 km. This creates a substantial footprint with significantly fewer sectors. A regional switching center controls all of the traffic within a market and interconnection with the Public Switched Telephone Network (PSTN). Capacity can be modularly upgraded by adding sectors to existing sites to facilitate subscriber growth.
4.3.3 Microcellular

Microcellular radio networks are used in areas with high traffic density, like suburban areas. The cells have radii between 200m and 1 km. For such small cells, it is hard to predict traffic densities and area coverage.

4.3.4 Picocells

Picocells or indoor cells have radii between 10 and 200m. Today, picocellular radio system are used for wireless office communications.

4.4 UMTS Architecture

4.4.1 General Architecture

Figure 4.1 shows the assumed UMTS architecture as outlined in European Telecommunication Standards Institute (ETSI)/SMG. The figure shows the architecture in terms of its user equipment (UE), UMTS Terrestrial Radio Access Network (UTRAN), and core network (CN). The respective reference points are Uu (radio interface) and Iu (CN-UTRAN interface) [6].

4.4.2 WCDMA for 3G Cellular Systems

Third-generation mobile radio networks have been under intense research and discussion recently and were scheduled to emerge in 2001. Emerging requirements for high-rate data services and better spectrum efficiency are the main drivers identified for these 3G mobile systems [6]. In the International Telecommunication Union (ITU), 3G networks are called International Mobile Telecommunications 2000 (IMT 2000), and in Europe, Universal Mobile Telecommunications Systems. The main objective of the IMT 2000 air interface can be summarized as follows:

- Full coverage and mobility for 144 Kbps, preferably 384 Kbps;
- Limited coverage and mobility for 2 Mbps;
- High spectrum efficiency compared to existing systems;
- High flexibility to introduce new services.

Wideband direct sequence code-division multiple access (DS-CDMA) has emerged as the mainstream air interface solution for the 3G networks
due to its numerous advantages over TDMA and frequency-division multiple access (FDMA). These advantages include the use of soft handover for macrodiversity, the exploitation of multipath fading through RAKE combining, and a direct capacity increase as a result of the use of cell sectorization. However, the air interface standardization seems to focus on two main types of WCDMA: network asynchronous and network synchronous.

In network asynchronous schemes, the base stations are not synchronized, whereas in network synchronous schemes, the base stations are synchronized to each other within a few microseconds. ETSI and the Association of Radio Industries and Businesses in Japan have chosen to develop a common WCDMA air interface standard, based on an asynchronous network for frequency-division duplex (FDD) bands.

The important concept of WCDMA is the introduction of intercell asynchronous operation and a user-dedicated pilot channel. Intercell asyn-
chronous operation facilitates continuous system deployment from outdoors to indoors. Other technical features of WCDMA are summarized next [6, 7; see also http://www.3gpp.org]:

- Fast cell search under intercell asynchronous operation;
- Fast transmit power control on both reverse (mobile-to-base station) and forward (base station-to-mobile) links;
- Coherent spreading code tracking;
- Coherent RAKE reception on both links;
- Orthogonal variable spreading factors in the forward link;
- Variable-rate transmission with blind rate detection;
- Data-rate-dependent transmit power.

The introduction of the data channel-associated pilot channel allows WCDMA to support interference cancellation and adaptive antenna array techniques that can significantly increase the link capacity and coverage. Table 4.1 lists the parameters of the WCDMA air interface standard [7].

Another major contender for the 3G WCDMA air interface standard, known as CDMA2000, is being developed by the Telecommunication Industry Association (TIA) in the United States. This chapter describes mainly the ETSI’s WCDMA air interface. However, a comparison of the WCDMA, CDMA2000, and the second-generation (2G) IS-95 CDMA systems is given in Table 4.2. The main differences between WCDMA and CDMA2000 systems are the chip rate, downlink channel structure, and network synchronization. Because WCDMA has an asynchronous network, different long codes rather than phase shifts of the same code are used for the cell and user separation. The code structure further impacts how synchronization, cell acquisition, and handover synchronization are performed.

### 4.5 Radio over Fiber Concept

A microcellular network can be implemented by using a fiber-fed distributed antenna network as shown in Figure 4.2. The received RF signals at each remote antenna are transmitted over an analog optical fiber link to a central base station where all the demultiplexing and signal processing are done. In this way, each remote antenna site simply consists of a linear analog optical transmitter, an amplifier, and the antenna. The cost of the microcellular
Table 4.1
Parameters of WCDMA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel bandwidth</td>
<td>(1,25), 5, 10, 20 MHz</td>
</tr>
<tr>
<td>Downlink $R_f$ channel structure</td>
<td>Direct spread</td>
</tr>
<tr>
<td>Chip rate</td>
<td>(1.024)/4.096/8.192/16.384 Mcps</td>
</tr>
<tr>
<td>Roll-off factor for chip shaping</td>
<td>0.22</td>
</tr>
<tr>
<td>Frame length</td>
<td>10 ms/20 ms (optional)</td>
</tr>
<tr>
<td>Spreading modulation</td>
<td>Balanced QPSK (downlink)</td>
</tr>
<tr>
<td></td>
<td>Dual channel (uplink)</td>
</tr>
<tr>
<td></td>
<td>Complex spreading circuit</td>
</tr>
<tr>
<td>Data modulation</td>
<td>QPSK (downlink)</td>
</tr>
<tr>
<td></td>
<td>BPSK (uplink)</td>
</tr>
<tr>
<td>Coherent detection</td>
<td>User-dedicated time-multiplexed pilot (downlink and uplink), common pilot in downlink</td>
</tr>
<tr>
<td>Channel multiplexing in uplink</td>
<td>Control and pilot channel time-multiplexed I and Q multiplexing for data and control channel</td>
</tr>
<tr>
<td>Multirate</td>
<td>Variable spreading and multicode</td>
</tr>
<tr>
<td>Spreading factors</td>
<td>4–256</td>
</tr>
<tr>
<td>Power control</td>
<td>Open and fast closed loop (1.6 kHz)</td>
</tr>
<tr>
<td>Spreading (downlink)</td>
<td>Variable-length orthogonal sequence for channel separation, Gold sequences $2^{18}$ for cell and user separation (truncated cycle 10 ms)</td>
</tr>
<tr>
<td>Spreading (uplink)</td>
<td>Variable-length orthogonal sequences for channel separation, Gold sequences $2^{41}$ for user separation (different time shift in I and Q channel, truncated cycle 10 ms)</td>
</tr>
<tr>
<td>Handover</td>
<td>Soft handover, interfrequency handover</td>
</tr>
</tbody>
</table>

antenna sites must be greatly reduced before the deployment of these networks is practical [11]. (More details are provided in Chapters 3 and 5.)

4.5.1 Advantages of Using RoF in Mobile Communications Networks

The radio network is a distributed antenna system, with the potential for adaptive antenna selection, as well as adaptive channel allocation to increase the spectrum efficiency. The distributed antenna system provides an infrastructure that brings the radio interface very close to the users and has the following benefits:

- Low RF power remote antenna units (RAUs);
- Line-of-sight (LOS) operation (multipath effects are minimized);
Table 4.2
Comparison of 2G and 3G CDMA Systems

<table>
<thead>
<tr>
<th></th>
<th>IS-95 CDMA</th>
<th>WCDMA</th>
<th>CDMA2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>1.25 MHz</td>
<td>5 MHz</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>9.6 Kbps</td>
<td>384 Kbps/2 Mbps</td>
<td>384 Kbps/2 Mbps</td>
</tr>
<tr>
<td>Chip rate</td>
<td>1.228 Mcps</td>
<td>4.096 Mcps</td>
<td>3.6864 Mcps</td>
</tr>
<tr>
<td>Frame length</td>
<td>20 ms</td>
<td>10 ms</td>
<td>20 ms</td>
</tr>
<tr>
<td>Packet and circuit</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>switch data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simultaneous data and</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>voice</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercell synchronization</td>
<td>Synchronous</td>
<td>Asynchronous</td>
<td>Synchronous</td>
</tr>
<tr>
<td>Spreading codes</td>
<td>Walsh + Long m-sequence</td>
<td>Variable-length orthogonal sequence + Gold sequence (10 ms)</td>
<td>Variable-length orthogonal sequence (Walsh) + M-sequence</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multirate capability</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Coherent detection</td>
<td>—</td>
<td>User-dedicated time-multiplexed pilot (downlink and uplink), common pilot in downlink</td>
<td>Pilot symbols time-multiplexed with PC bits (uplink), common continuous pilot channel and auxiliary pilot</td>
</tr>
<tr>
<td>Handover</td>
<td>Soft handover</td>
<td>Soft handover, interfrequency handover</td>
<td>Soft handover, interfrequency handover</td>
</tr>
<tr>
<td>Power control</td>
<td>Reverse open and fast closed PC, forward slow control loop</td>
<td>Forward and reverse, open and fast closed loop (1.6 kHz)</td>
<td>Forward and reverse, open and fast closed loop</td>
</tr>
</tbody>
</table>

- Enabling of mobile broadband radio access close to the user in an economically acceptable way;
- Reduced environmental impact (small RAUs);
- Good coverage;
- Capacity enhancement by means of improved trunking efficiency;
- Dynamic radio resource configuration and capacity allocation;
- Alleviation of the cell planning problem;
• Reduction in the number of handovers;
• Centralized upgrading or adaptation;
• The potential to deploy precision tracking of user equipment for safety/first aid and other purposes;
• Higher reliability and lower maintenance costs;
• Support for future broadband multimedia applications;
• Better coverage and increased capacity;
• High-quality signals;
• Support for macrodiversity transmissions;
• Low fiber attenuation (up to 0.2 dB/km);

Figure 4.2 Optically fed remote antenna network for microcellular RoF systems.
The use of low RF power RAUs has these benefits:

- Low generated interference;
- Increased spectrum efficiency;
- Easier frequency/network planning;
- Increased battery lifetime of mobile terminals;
- Relaxed human health issues;
- The potential to use RF complementary metal oxide semiconductor technology in mobile terminals.

A multioperator shared infrastructure allows for equal performance and power levels (the problem with uncoordinated mobiles would be alleviated).

### 4.5.2 Radio over Fiber Application in Microcellular Systems

Recently, the use of optical fiber feeders for alleviating the problems inherent in microcellular systems has attracted much attention. The goals of the microcellular mobile communication systems include service availability over an extremely high percentage of user environments and provision of a combination of services such as voice, data, and multimedia. Provision of such enhanced services at a high-quality level of service requires an expensive remote antenna (base station) density of tens, hundreds, or even thousands of antennas per square kilometer. This antenna density enables more subscribers to be accommodated per unit service area and allows for the use of smaller and lower power handsets.

To make the base stations compact and cost-effective, it has been proposed that the RoF technique be used to transfer the complicated RF modem and signal processing functions from the base stations to a centralized control station. The proposed fiber-feeder microcellular system is shown in Figure 4.3. The microbase stations will consist mainly of a photodiode circuitry (O/E), RF power amplifier (PA) in the forward link, and a low-noise amplifier (LNA) laser diode circuitry (E/O) in the reverse link [12, 13].
4.5.3 Simulation Approach and Model Components

In this section, a simulation approach is used for the handover performance evaluation. Figure 4.4 shows the components of the proposed simulation model for the analysis. A microcellular cell plan in the Manhattan-type environment [14], as illustrated in Figure 4.5 (i.e., full-square cell plan), is used for the WCDMA RoF systems. The proposed cell plan will offer the following benefits:

![Diagram of proposed simulation model components for analysis of soft handover algorithms in WCDMA RoF networks.](image)

**Figure 4.4** Proposed simulation model components for analysis of soft handover algorithms in WCDMA RoF networks.
Figure 4.5 Manhattan-type environment.

- Reduced rate of handover;
- Reduced number of base stations and signaling load for RoF systems employing network control handover with soft handover;
- Enhanced handover execution delay, based on the fact that handover will occur only at street junctions where high-speed mobiles are assumed to have slowed down.

4.6 Simple Simulation Model of WCDMA RoF System

The simulation model of the downlink WCDMA RoF system using SystemView is as shown in Figure 4.6. It consists of one dedicated physical data channel and the synchronization channels, of which the primary SCH level is used to select the strongest base station using a match filter in the mobile unit. The transmitting filter is a raised cosine filter with a roll-off factor of 0.22. The laser diode is modeled as a third-order polynomial. The
optical fiber is modeled as an attenuator at 0.2 dB/km. The maximum fiber length is assumed to be 1 km (i.e., the furthest remote antenna location from the serving central base station). A p-i-n photodiode responsivity of 0.8 is assumed. The RF power amplifier gain is set at 10 dB. The radio channel is modeled as Rician for the desired signal and the interfering signals.

### 4.6.1 The Optical Fiber Link Model

A model of the laser that predicts laser performance in an analog transmission environment has been developed as shown in Figure 4.7.

The combination of WCDMA and RoF represents a first demonstration of new broadband applications using the full radio over fiber environment. A key component in the system is the laser diode. The nonlinear nature of the light source is obtained from modeling of both memoryless and laser rate equations. The simulation of a single microcell WCDMA system with a power control and soft handover subsystem is used to determine the effects of the optical link on the performance of the power control and soft handover subsystem. The simulation model has provided accurate results and is simple in order to be efficient in simulating such a complex environment.
The simulation package SystemView has been used to construct a hierarchical simulation model. The simulation model consists of mainly four parts:

1. The RF WCDMA network consists of one microcell base station and a number of uniformly distributed mobile stations where the air channel will be modeled as a Rician fading channel with log-normal shadowing and fourth-power path loss.

2. The calls generator randomly generates requests for mobile connections and can be specified by a number of random parameters: the speed and direction of the mobile station(s) (Gaussian), the location of the mobile stations relative to the microcell (uniform), and the call interval (Gaussian).

3. The optical link model uses parameters that have already been identified from experimental work.

4. The power control subsystem model is based on the Third-Generation Partnership Project (3GPP) standards.

The aim of the simulation model is to have an integrated model for both wireless and optical systems that would be transparent to a different system such as GSM, UMTS, and High-Performance Radio Local Area Network type 2 (HiperLAN2) as shown in Figure 4.8. The interface between the core network and the optical premises network (the multiaccess optical network) would be an office or a residential gateway with a common access platform, which would include the radio base station (RBS).
4.7 Macrodiversity Versus Microdiversity

In microdiversity, multiple antennas are employed at the receiver to form the branches for the diversity combiner. Microdiversity is used to combat small-scale fading induced by the channel at the receiver. Microdiversity has also been used to realize space-division multiple access (SDMA) communications systems. In these systems, all users transmit simultaneously on a single channel, and a user’s physical location is used to separate the desired signal from the interference. The diversity antennas are used to effectively create a steerable beam that selects the desired user’s signal while suppressing interference from the other users.

SDMA systems involving microdiversity techniques have been successfully developed and demonstrate the potential of using microdiversity to improve capacity on a single channel. The distance between the antennas in the microdiversity system is of the order of only a few wavelengths [15]. Macrodiversity is another realization of space diversity in cellular systems. Like microdiversity, macrodiversity is used to improve the S/N of the received signal. However, the diversity branch signals in a macrodiversity system originate from the base station antennas, instead of an array of antennas at the receiver as in a microdiversity system. Hence, the main difference between branch signals received in a macrodiversity system versus those in a microdiversity system is the amount of attenuation and time delay on the received signals.
Macrodiversity is useful for combating shadowing of a user’s signal caused by obstructions in the environment. To this end, macrodiversity has been employed in CDMA systems to improve signal quality near cell boundaries during soft handover. However, macrodiversity has not been widely targeted as a method for reducing interference in communications systems. Furthermore, systems employing macrodiversity have not considered diversity techniques involving combining of signals on the reverse link [16, 17].

4.7.1 Macrodiversity Combining for the Uplink

Although macrodiversity techniques have been employed in modern cellular systems, techniques that employ combining have not been explored as a means of reducing interference in these systems. In WCDMA, the use of more sophisticated techniques could significantly reduce multiple-access interference and extend the capacity of current and next-generation systems [17].

To combat the interference problem, power control of the mobiles is employed so that users close to the base station do not overwhelm those who are farther away [9]. Soft handover is employed whereby a mobile communicates with two or more base stations when making a transition from one cell to another. Soft handover improves the quality of the link by using signal diversity to improve the S/N of the received signal. On the forward link, multiple base stations transmit the same signal to a mobile terminal, which aligns, cophases, and combines the signals to improve the S/N. On the reverse link, the quality of the link is improved by selecting the best signal received from a set of base stations in the vicinity of the mobile terminal [18].

The use of selection diversity on the reverse link suggests that there could be a substantial capacity improvement if a combining technique were used, because selection diversity offers a limited increase in signal quality compared to these techniques.

4.7.2 Macrodiversity Architecture in Radio over Fiber

The design of a radio over fiber microcellular system with macrodiversity schemes should consider the effect of the optical fiber link. The noise of the optical fiber link is relatively small compared to that of a wireless link. Because the processing will be carried out at the central base station, the macrodiversity can be realized very easily, as shown in Figure 4.9.
the degradation caused by fading is expected to be improved. The signal
received by the mobile station is the sum of the faded transmitted signal
and the optical fiber link noise. The parameters that need to be considered
in implementing an analog fiber optic system are C/N, bandwidth, and
signal distortion resulting from nonlinearity in the transmission system.

4.7.3 Simulation Model

The main components, which are essential for the investigation of the
macrodiversity architecture in radio over fiber, are shown in Figure 4.10.

The propagation model for the radio link must consider the path loss,
signal fading, and multiuser interference. For the fiber link, it is considered
the loss in the fiber and laser nonlinearity.

4.8 Estimation of Number of Downlink Traffic Channels
per RF Channel

From spread-spectrum communications theory and in an ideal case, the
number of CDMA channels that can be multiplexed in a given bandwidth

Figure 4.9 CDMA signal in an optical fiber link.

Figure 4.10 Simulation model components.
is equal to the ratio of the spreading code chip rate to the data rate. For a chip rate of 3.84 Mcps and data rate of 384 Kbps, for example, this would result in 10 possible CDMA channels per carrier—theoretically. Beyond this limit the multiplexing capability of the system collapses catastrophically unless special techniques are used such as multiuser detection. In practice, especially for a multicell microcellular mobile communications system, the situation is far from ideal.

It may well be close to impossible to actually determine the number of possible traffic channels per RF channel. However, simulation techniques can be utilized to find a rough estimate based on orthogonality factor $\alpha$, which is given by [6]:

$$\alpha = 1 - \frac{E_b}{I_0} \left( \frac{E_b}{N_0} \right)^{-1}$$ (4.1)

where $I_0$ is intracell interference and $N_0$ is intercell interference. The block diagram of such a downlink simulation is shown in Figure 4.11.

From such simulations that can be found in the literature, the orthogonality factor is found to be equal to 0.7 in the microcellular environment. From other spectrum efficiency simulations for the downlink utilizing the CODIT microcell channel model, the corresponding spectrum efficiency is found to be 300 Kbps/MHz/carrier. For a 5-MHz bandwidth, this is 1.5 Mbps/carrier, which is equal to 3.9 users with 384-Kbps service. In our calculation five simultaneous users are assumed in order to count for the pilot, synchronization, and paging channels in the downlink. These simultaneous users are distributed arbitrarily throughout a given cell. For the purpose of calculating the required transmission (Tx) power per channel, the worst situation is assumed. All users are situated at the edge of the cell, hence requiring maximum transmission power. Therefore:

![Figure 4.11 Block diagram of a downlink simulation.](image-url)
Tx power per channel = 5 (average transmitter power per traffic channel)

or, in decibels,

$$\text{Tx power per channel} = P_{\text{TX,avg}} + 7$$

The resulting figures are 19.34 and 38.05 dBm for the urban and suburban scenarios, respectively.

### 4.9 Spectral Efficiency, Power Level, and Projected Number of Users

In microcellular systems the number of users $N$ is given by [6]:

$$N = F \left( G_{p} \left( \frac{E_{b}}{N_{0}} \right)^{-1} - (\beta - 1) \right) \left( 1 - F \beta \right)^{-1}$$  \hspace{1cm} (4.2)

where $F$ is the fraction of the intracell interference to the total interference, $G_{p}$ is the processing gain of the link (= 10 dB in the 384-Kbps case), $\beta$ is the multiuser detection efficiency (= 0% if no multiuser detection), and $E_{b}/N_{0}$ is the energy per bit to power spectral density ratio.

In the case of RoF the noise power spectral density will increase by an amount that is proportional to the optical link $NF$, forcing a higher required $E_{b}$ (power level). In our calculations the difference in $E_{b}$ between the wireless and RoF systems is less than 1 dB.

#### 4.9.1 Network Capacity

The capacity is strongly dependent on the radio environment, which is defined by the path loss attenuation factor, shadowing, and wideband channel. The capacity gain depends on the intracell to total interference ratio ($F$), as in (4.2).

#### 4.9.2 Dynamic Range

In our opinion we anticipate that the dynamic range required for the WCDMA system is much lower than the required dynamic range for the
GSM system. This is due to the high-performance power control system in the WCDMA. This system is much faster (1,500 updates per second) and more comprehensive than any other power control system. In addition, the required power level in WCDMA is much lower than in the GSM system.

### 4.10 WCDMA-Based RoF System Performance with Multiple-User Interference

This section is intended to investigate the effect of voice activity monitoring on multiple-user interface, intermodulation distortion, and clipping noise power and the overall performance of WCDMA RoF systems in multiple-service transmission. In addition, this section provides a simple analytical model for estimating intercell interference power density ($I_{\text{ter}}$), using minimum path attenuation criteria. The model proposed in this section is based on a valid assumption that poses much less computational complexity compared with other models used elsewhere in the literature.

#### 4.10.1 WCDMA RoF System Configuration

The uplink of the WCDMA RoF system configuration is shown in Figure 4.12. It consists of the radio link, which is based on the WCDMA air interface, and the optical link. A detailed description of the uplink WCDMA

![Diagram of WCDMA RoF system](image)

*Figure 4.12* WCDMA RoF system. (LD: laser diode; PD: photodiode.)
system is not given in this chapter, but can be found in [6, 7]. Basically, the WCDMA is a multiple-service and multiple-rate system. Thus, each user can transmit a number of different services with variable data rates on dedicated physical data channels (DPDCH), plus a common dedicated physical control channel (DPCCH). The data symbols on DPDCH and DPCCH are independently multiplied (spread) with an orthogonal variable spreading factor on the so-called I and Q branches. The resultant signals on the I and Q branches are further multiplied by a user-unique but complex-valued long/short scrambling code $C_{sc}$, where I and Q denote real and imaginary parts, respectively. The complex-valued chip sequence (i.e., 3.84 Mcps) generated by the spreading process is QPSK modulated and transmitted on carrier frequency $\omega_c$, in the radio channel.

By neglecting multipath propagation effects on the transmitted signals, we can express the total received signal at the base station from $N$ users as

$$I(t) = \sum_{i=1}^{N} \sum_{s=1}^{M} \varphi^I_s d^I_s(t - \tau_{i,s}) C_{sc,i}(t - \tau_i) \sqrt{2P_i} \cos[\omega_c(t + \tau_i) + \theta_i]$$

(4.3)

where $M$ is the number of $i$th user’s multiple services, $\varphi^I_s$ is the weighted gain factor on each multiple service channel, $P_i$ and $\theta_i$ are the carrier power and phase, respectively, of the $i$th user. Also, $\theta_i$ is assumed to be uniformly distributed in $[0, 2\pi]$. $\tau_i$, $\tau_{I,s}$ are random variables that model the asynchronous transmission of users and their respective service type signals to the base station, respectively, which are also assumed to be uniformly distributed in $[0, T]$. $d^I_s(t) = \sum_{j=-\infty}^{\infty} d^I_{s,j} P_T(t - jT)$ is the data stream of the $i$th user’s $s$th service type. The term $d^I_{s,j}$ takes the binary values $\pm 1$ with equal probability in the interval $[jT, (j + 1)T]$, where $T$ is the symbol period and $P_T$ is a rectangular pulse, which equals unity for $0 \leq t \leq T$ and zero otherwise. $C_{sc,i}(t)$ and $C^i_{ch,s}(t)$, the orthogonal variable spreading factors, are given here, respectively, as

$$C_{sc,i}(t) = \sum_{l=-\infty}^{\infty} c_{sc,i,l} P_T(t - lT_c)$$

(4.4)

$$C^i_{ch,s}(t) = \sum_{l=-\infty}^{\infty} c^i_{ch,s,l} P_T(t - lT_c)$$

(4.5)
where $C_{ch,s,l}^i$ and $C_{sc,f,l}^i$ are real and complex-valued chip sequences that take values $\pm 1$ in the interval $[lT_c, (l + 1)T_c]$, and $P_{T_c}(t)$ is a rectangular pulse, which equals unity for $0 \leq t \leq T_c$, and zero otherwise. $T_c$ is the chip rate. With a spreading factor (i.e., processing gain) of $G$, $T = GT_c$. At the base station the signal in (4.3) is used to direct modulate the optical intensity of the laser diode (i.e., electrical-to-optical conversion) and transmitted through the fiber cable to the central base station for processing. The laser diode nonlinearity can be modeled by a third-order polynomial without memory to give the output optical signal as $[2, 19, 20]$:

$$P(t) = P_t[1 + I'(t) + a_2I'^2(t) + a_3I'^3(t)] + \eta(t) \quad (4.6)$$

Here $P_t$ is the average transmit optical power, $I'(t) = I(t)/(I_b - I_{th})$, where $I_b$ and $I_{th}$ are the laser-diode bias and threshold current, respectively; $a_2$ and $a_3$ are the second- and third-order coefficients, respectively; and $\eta(t)$ is background noise.

### 4.10.2 Intermodulation Distortions and Clipping Noise

The CDMA system’s capacity is known to be interference limited; therefore, any reduction in interference will lead to direct increase in capacity. In WCDMA RoF systems, apart from intracell interference power ($I_{tra}$) and intercell interference power ($I_{tet}$), another source of interference is due to laser diode nonlinearity. The laser diode nonlinearity causes mixing of users’ signals, resulting in generation of harmonics and intermodulation distortions. Because the second-order intermodulation terms generate zero frequency and the double-frequency components, and the third-order term generates the common frequency and the triple-frequency components, only one harmonic of the third-order term influences the system performance (i.e., $2f_1 - f_2 = f$, since $f_1 = f_2 = f$) $[8]$. Therefore, the intermodulation distortion (IMD) noise can be assumed to be part of the multiple-user interface. As a result the total intracell interference power can be given as $I_{traT} = I_{tra} + \sigma^2_{imd}$. An expression for third-order intermodulation distortion power of random sequence CDMA in optical transmission systems has been derived in $[10]$ as:

$$\sigma^2_{imd} = \frac{(\rho P_r m)^2}{2} \left\{ \frac{a_3 m^2(2N - 1)(N - 1)}{2G} + \frac{a_3^2 m^4(N - 1)}{64} \right\} \left( 9 + \frac{126N^2 + 30N - 264}{5G} - \frac{15(N - 2)}{G^2} \right) \quad (4.7)$$
where $\rho$ is photodiode responsivity, $m$ is the optical modulation index, and $P_r$ is the average received optical power. When considering a perfect power control, $I_{\text{tra}}$ can be given as [10]:

$$I_{\text{tra}} = (\rho m_0 P_r)^2 \frac{N - 1}{12G}$$  \hspace{1cm} (4.8)

In [5] the expression for the variance of clipping impulsive noise was assumed to be

$$\sigma_{\text{clip}}^2 = \frac{I_p^2 m^6 N^3}{27.2} \exp \left( -\frac{1}{2m^2 N} \right)$$  \hspace{1cm} (4.9)

### 4.10.3 Intercell Interference Model

In cellular systems even cell ownership for users is difficult to determine due to shadowing effects. As a result two types of intercell interference scenarios may be possible, as shown in Figure 4.13: interference from mobiles located in their home cells to adjacent cells, and interference from mobiles located in one cell but communicating with a base station in another cell. This could happen, for instance, during handover initiation. Assuming perfect power control, the power control algorithm is such that the transmitting power of mobile unit $m_2$ in Figure 4.13 to the base station $B_2$ will be

$$S_t = S_r r^\beta e^{-\xi \ln(10)/10}$$  \hspace{1cm} (4.10)

![Figure 4.13](image-url) **Figure 4.13** Intercell interference scenarios. The bold lines and broken lines indicate the desired links and interference links, respectively.
where \( S_r \) is the desired receive power at B2, \( r \) is the distance from the m2 to B2, \( \beta \) is the path-loss exponent, and \( \xi \) is a Gaussian random variable with zero mean and standard deviation \( \sigma \), representing the log-normal shadowing. Supposed that \( \zeta \) is the shadowing effect on the path m2 to B1, then the normalized interference power generated at B1 due to m2 will be given as

\[
\frac{I_{\text{ter}}}{S_r} = y^{-\beta} e^{-\xi \ln(10)/10} < 1 \tag{4.11}
\]

Otherwise, m2 should switch its transmission to B1. We also assumed a circular cell structure with uniform distribution of users in the cells and user density/cell given as

\[
\eta = \frac{N}{\pi R^2} \tag{4.12}
\]

where \( R \) is the cell radius. The total normalized intercell interference power is obtained by integrating over the total area of the interfering cells:

\[
\frac{I_{\text{ter}}}{S_r} = \eta \alpha q \int_0^{(D+R)} \int_0^\pi (y)^{-\beta+1} e^{-\zeta \ln(10)/10} \, dA \tag{4.13}
\]

\[
= 2\eta \alpha q \int_0^{(D+R)} \int_0^\pi (y)^{-\beta+1} e^{-\zeta \ln(10)/10} \, dx \, d\theta
\]

where \( q \) is the number of interfering cells.

The expected intercell interference power can be expressed similarly to [9] as

\[
E\left( \frac{I_{\text{tra}}}{S_r} \right) = 2\eta \alpha q \int_0^{(D+R)} \int_0^\pi (x)^{-\beta+1} E[e^{-\zeta \ln(10)/10} f(x, \zeta)] \, dx \, d\theta
\]

From the condition in (4.11) we can assume \( \zeta = 40 \log(y) \) as the worst case interference. Therefore,

\[
f(\zeta, y) = \begin{cases} 
1 & \text{if } \zeta \leq 40 \log(y) \\
0 & \text{otherwise}
\end{cases} \tag{4.15}
\]
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\[ E[e^{-\xi \ln(10)/10} f(\xi, y)] = \frac{1}{\sqrt{2\pi} \sigma} \int_{-\infty}^{40 \log(y)} e^{-\xi \ln(10)/10} e^{-\frac{\xi^2}{2\sigma^2}} d\xi \]

where

\[ = e^{[\sigma \ln(10)/10]^2} \frac{40 \log(y)}{\sqrt{2\pi} \sigma} \int_{-\infty}^{\infty} \text{Exp} \left[ -\frac{1}{2} \left( y/\sigma - \sigma \ln(10)/10 \right)^2 \right] dy \]

\[ = e^{(\sigma \ln(10)/10)^2} \left\{ 1 - \frac{1}{2} \left[ 1 - \text{erf} \left( \frac{40 \log(y)}{\sigma \sqrt{2}} - \frac{\sigma \ln(10)}{10 \sqrt{2}} \right) \right] \right\} \]

(4.16)

where \( \text{erf}(\cdot) \) is the error function. Substituting (4.16) in (4.14), the resulting equation can be integrated numerically.

4.10.4 System Performance

In WCDMA RoF systems the transmission quality specification can be expressed in terms of energy per bit over the total interference and noise power density (ENR) of the dedicated traffic channel as

\[ \frac{E_b}{N_t} = \frac{G(mpP_r)^2/2}{I_{\text{tra}}(1 + I_r)\alpha + \eta} \]

(4.17)

where \( \alpha = 3/8 \) is the voice activity factor; \( I_r \) is the intercell interference factor, defined as the ratio of \( I_{\text{ter}} \) and \( I_{\text{tra}} \) are background noise, \( \eta \) in RoF systems include RIN \( I_p^2 \), laser relative intensity noise (taken to be \(-155 \text{ dB/Hz}\)); \( 2eI_p \), shot noise due to photodetector; \( \sigma^2_{\text{clip}} \), clipping noise variance; \( \sigma^2_{\text{imd}} \), intermodulation noise variance; and \( <I_t^2> \), thermal noise equivalent power referred to the optical receiver front end (\( I_t = 10 \text{ pA/\sqrt{Hz}} \)) [2]. Thus, \( \eta = [(\text{RIN} \cdot I_p^2 + 2eI_p + <I_t^2>)B + \sigma^2_{\text{imd}} + \sigma^2_{\text{clip}}] \), with \( B = 5 \text{ MHz} \) as the bandwidth and \( I_p = \rho P_t 10 - \gamma L/10 \), where \( P_t = 5 \text{ mW} \) is the average transmitting optical power, \( \gamma = 0.2 \text{ dB/km} \) is fiber loss [21], and \( L = 10 \text{ km} \) is the fiber length used in this analysis. When using voice activity monitoring, the probability that \( k \) out of \( n \) interfering users are active can be described by a binomial distribution [8, 9]:
\[ P(n, k) = \binom{n}{k} \alpha^k (1 - \alpha)^{n-k} \] (4.18)

Note that here \( n \) represents the number of voice channels out of the total number of multiple service channels, \( N \) (voice + data). Now, considering the effect of voice activity monitoring on intermodulation distortion and clipping noise power, (4.17) can be rewritten as

\[
\frac{E_b}{N_t} = \frac{G(m_o \rho P_r)^2/2}{\left\{ [(I_{\text{tra}} + \sigma^2_{\text{imd}}) + \sigma^2_{\text{clip}}] (I + I_r) \right\} \delta + [\text{RIN} \cdot I_p^2 + 2eI_p + <I_{\text{th}}^2>] B} 
\] (4.19)

Here \( \delta = [\alpha + (1 - \alpha)x] \) is a factor that accounts for the effective voice activity factor due to multiple-service transmission, where \( 0 \leq x \leq 1 \) is the percentage ratio of data channels out of the total number of service channels, \( N \).

### 4.10.5 Results and Discussions

The results presented in this analysis are based on a three-tier \( (q = 36 \text{ cells}) \) microcellular system with \( R = 100 \text{m}, \sigma = 10 \text{ dB}, \) and \( \beta = 4 \), giving \( I_r = 0.1 \). The ENR dependence on the number of data channels \( x \) and modulation index \( m \), with and without the voice activity effect on intermodulation distortion and clipping noise, is shown in Figures 4.14 and 4.15, respectively. We also assumed that the data channels, unlike the voice channel, are transmitted continuously. We can see from Figure 4.14 that up to a 4.5-dB improvement in ENR performance can be achieved when taking into account the effect of voice activity on intermodulation distortion and clipping noise. It is worth noting, however, that the performance decreases with decreasing \( m \) and increasing \( x \), whereas in Figure 4.15 the ENR remains constant, irrespective of \( x \), at high values of \( m \). The effect of voice activity becomes perceptive only at low \( m \). The reason for this behavior is that, at \( x = 0 \), although only voice channels are being transmitted, the effect of voice activity on the multiple-user interface is being compensated for by high intermodulation distortion and clipping noise due to a high modulation index. Also, at \( x = 1 \) there is no voice activity monitoring or only data channels are being transmitted, but a high modulation index with high intermodulation distortion and clipping noise generally results in a low ENR. Clearly, it can be seen that this noise compensation behavior changes with decreasing modulation index.
Figure 4.14 ENR dependence on $m$ and $x$ for $N = 30$ with voice activity monitoring effect on intermodulation distortion and clipping noise at $G = 256$.

Figure 4.15 ENR dependence on $m$ and $x$ for $N = 30$ without voice activity monitoring effect on intermodulation distortion and clipping noise at $G = 256$.

It is obvious from Figure 4.15 that, in WCDMA RoF systems voice activity monitoring becomes ineffective when operating at a high modulation index if we ignore the effect of voice activity monitoring on intermodulation distortion and clipping noise. These results can be misleading because they can lead to overestimation of ENR requirements for voice and data services, which could consequently impact the link budget.
Results of ENR dependence on processing gain $G$ and $x$, with and without voice activity effect on intermodulation distortion and clipping noise, are shown in Figures 4.16 and Figure 4.17, respectively. We can see from Figure 4.16 that ENR decreases with decreasing $G$ and increasing $x$, whereas in Figure 4.17, again the ENR increases with $G$, but remains constant with respect to $x$ at $m = 0.25$ for the same reasons given above.

4.11 Radio over Fiber for HiperLAN2 Microcellular Communication Networks

Today’s typical local area network (LAN) environment requires costly planning and investments to build and maintain. Data exchange between computers occurs at present over wireline LANs. Wireless technology will make it less demanding to move computer equipment to new locations that lack easy access to LAN cables. Wireless technology has enjoyed increased demand from the general public as well as from business and other professional users. The demands for the wireless technology range from use in cellular phones...
to high-speed digital networks supporting high-speed computer communications. At present, standards for broadband wireless multimedia communications in the 5-GHz band are being developed in Europe as well as in the United States and Japan. HiperLAN2 is an upcoming standard that is being specified by the ETSI/BRAN project. HiperLAN2 is one of the wireless broadband access networks and will provide high-speed communications with a bit rate of at least 20 Mbps between mobile terminals and various broadband infrastructure networks.

Currently a strong alignment exists among the three standardization bodies, IEEE 802.11a (United States), ETSI/BRAN (Europe), and MMAC (Japan) on the physical layer. This agreement provides a worldwide platform for broadband wireless multimedia communications, whereas the upper layer protocols are different. The three systems in Europe, the United States, and Japan will operate at the 5-GHz band. In addition, all have adopted orthogonal FDMA with 64 subcarriers, where 48 subcarriers are used for data and 4 are used for pilot signals (which eases phase tracking for coherent demodulation); the remaining 12 subcarriers are set to zero [22–27].

HiperLAN2 is intended to provide local wireless access to, for example, IP, ATM, and UMTS infrastructure networks by using both moving and
stationary terminals that interact with access points, which, in turn, are usually connected to an IP, ATM, or UMTS backbone network, as shown in Figure 4.18. A typical HiperLAN2 system consists of a number of access points connected to a backbone network, for example, an Ethernet LAN. An access point can use an Omni antenna, a multibeam antenna, or a number of distributed antenna elements. The system supports mobility between access points on the same backbone network; that is, handover is made between access points. Figure 4.18 shows the HiperLAN2 system architecture.

Mobile terminals are associated with access points, where each access point is connected to a backbone network; for this example it is an Ethernet backbone [26–28; see also http://ieeexplore.ieee.org/lpdocs/epic03/, http://www.hiperlan2.com/web/, and http://www.networkcomputing.com]. Such wireless access networks will be able to provide the quality of service that users expect from a wired IP or ATM network.

The introduction of the fiber into HiperLAN2 will mean that the antenna of the HiperLAN2 access point could be distributed, which leads to an increased number of coverage areas and, hence, increased capacity and improved performance from a single access point. The coverage areas of both systems (with and without the fiber) will be different; in fact, the system with the fiber link will have less coverage area per antenna, but the area per access point will be larger, as shown in Figure 4.19.

As the mobile terminal moves out from the serving access point toward the neighboring cell, it will establish a second parallel link, at a different

![Figure 4.18 HiperLAN2 system overview.](image-url)
time slot allocation, from the ongoing access point before releasing the old link with the previously serving access point [http://www.hiperlan2.com/web, http://www.networkcomputing.com, http://www.telecomnames.com/, and http://www.nokia.com/corporate/wlan/index.html]. At the moment when new parallel link is received, the mobile terminal can then communicate with both access points, receiving data from the two access points, by allocating time slots by each access point. The phenomenon of receiving the data from two neighboring access points is called *macrodiversity*. The advantage that can be obtained from macrodiversity is the increase of the S/N at the single access point, resulting in a corresponding capacity increase.

The structure of the HiperLAN2 system without the fiber is shown in Figure 4.19(a). The problem with this structure is that, as the mobile terminal communicates with two access points, the signals cannot be combined due to the separation of the access point’s transceivers. If the fiber is included, the antennas can be distributed and controlled by a single access point. This is a great advantage of the mobile terminal communicating with two access points; therefore, a maximum ratio combining could be obtained in the uplink to improve system capacity. More investigations are under way to forward our understanding of the requirement for this 4G technology.

**4.12 Conclusions**

The general concepts of CDMA/WCDMA radio over fiber systems have been presented. A simple simulation model of the downlink segment of a
WCDMA radio over fiber system was presented using SystemView. A definition for the macrodiversity architecture and radio over fiber was also presented. The concepts of the cellular architecture and the UMTS were explained along with the role of the macrodiversity function in the UMTS architecture. A model for the macrodiversity function and algorithms has been developed.

A simulation model of the multipath WCDMA using SystemView to investigate the performance of the macrodiversity function was developed. An analytical model for evaluating the performance of WCDMA-based radio over fiber systems has been presented. We have shown that up to a 4.5-dB improvement in ENR can be achieved if we take into account the effect of voice activity monitoring on intermodulation distortion and clipping noise due to laser diode nonlinearity. The performance variation with respect to modulation index and processing in multiple-service transmission gain has also been investigated. The results are useful for determining the optimum modulation index and for conducting capacity analyses and link budget estimations. Finally, the 4G applications of radio over fiber with HiperLAN2 were presented.

References


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