CHARACTERISTICS AND COMPENSATION OF MULTIPATH PROPAGATION IN BROADBAND WIRELESS ACCESS SYSTEMS

Hikmet Sari(1), (2) and Fabien Buda(2)

(1)SUPELEC, Plateau de Moulon, 3 rue Joliot-Curie, 92192 Gif-sur-Yvette Cedex, France
Email: hikmet.sari@supelec.fr

(2)SEQUANS Communications, 101 – 103 boulevard Mac Donald, 75019 Paris, France
Email: fabien@sequans.com

ABSTRACT

Broadband wireless access (BWA) at microwave frequencies between 2 and 11 GHz is a promising technology for both business and residential applications. Propagation in these systems is not strictly line-of-sight (LOS), and the multipath propagation encountered leads to very large channel dispersions. The technical specifications recently developed by the IEEE 802.16 group for this application include three different technologies, which are orthogonal frequency-division multiplexing (OFDM), orthogonal frequency-division multiple access (OFDMA), and single-carrier transmission (SCT), three technologies which can efficiently cope with long channel dispersions provided the latter uses frequency-domain equalization (FDE). This paper discusses the propagation problems in BWA at frequencies between 2 and 11 GHz and describes the technologies used in the IEEE standards. We also discuss the optional diversity and multiple antenna techniques, which enhance performance and capacity.

Keywords: Broadband wireless access, IEEE 802.16, WiMax, OFDM, OFDMA.

1. INTRODUCTION

Broadband wireless access (BWA) was originally viewed as a technology for delivering service to fixed business and subscriber user premises, i.e., an alternative to asymmetric digital subscriber lines (ADSL) and cable modem technologies. But more recently, there has been a shift in the service requirements to cover mobile user terminals, and the technical specifications were updated accordingly.

Technical specifications for BWA were drafted by the IEEE 802.16 Group, which addressed the 10-66 GHz millimeter-wave frequency band in a first phase and the 2-11 GHz microwave band in a second phase [1]. In the millimeter-wave frequency band between 20 and 45 GHz, there is a wide spectrum usable for this application, but unfortunately, millimeter-wave radio technology is still not mature enough to make BWA systems at these frequencies viable for residential applications. Therefore, millimeter-wave BWA systems are primarily intended to business customers in urban or suburban areas with high user density, and their commercial deployment remains very small scale. To address the residential subscriber market and compete with digital subscriber lines (DSL) and cable modems, as well as with other emerging wireless technologies, attention was therefore turned to microwave frequency bands between 2 and 11 GHz, where low-cost radio technologies are available. These bands include the 2.5 GHz microwave multi-point distribution service (MMDS) band in the US, the 3.5 GHz band all across Europe, and the 10 GHz band, which is available in a number of countries in Europe, Latin America, and some other regions.

But although it has been a hot topic for almost a decade, BWA is still in its infancy. Equipment cost is obviously one of the reasons, but this slow development can also be attributed to the lack of industry standards in the past. Fortunately, the IEEE 802.16 standard developed for fixed services and the more recent IEEE 802.16e standard [2] developed for mobile applications close this gap. In addition, the establishment of the WiMax Forum, which gathers many service providers, network operators, equipment manufacturers and technology companies, is a clear indication that there is today a strong interest in BWA for fixed and mobile applications, and commercial deployments are planned for early 2006.

This paper addresses multipath propagation problems in BWA systems at microwave frequency bands between 2 and 11 GHz and discusses the technologies adopted in industry standards. First, in the next section, we give a brief introduction to BWA in these frequency bands, discuss the propagation problems and present the channel models used. Next, in Section 3, we describe the transmission and multiple access techniques adopted in the recent IEEE 802.16 and IEEE 802.16e specifications. Then, in Section 4, we briefly discuss diversity and multiple input/multiple output (MIMO) techniques and give some performance results. Finally, we give some conclusions in Section 5.

2. BWA AT MICROWAVEVE FREQUENCIES BELOW 11 GHZ

2.1. A Brief Review

Fixed BWA takes the form cellular network, where each base station (BS) serves a number of subscribers located in its coverage area. Since the subscriber locations are fixed, each user is assigned to a predetermined BS (typically the nearest BS) and directional subscriber antennas are pointed to the serving BS during installation. The increased gain in the direction of the serving BS reduces network interference on one hand and increases cell coverage on the other hand. Fig. 1 shows a rectangular cell pattern with 90° cell sectoring, where the A, B, C, D labels indicate the 4 sectors around each base station as well as the channels used.

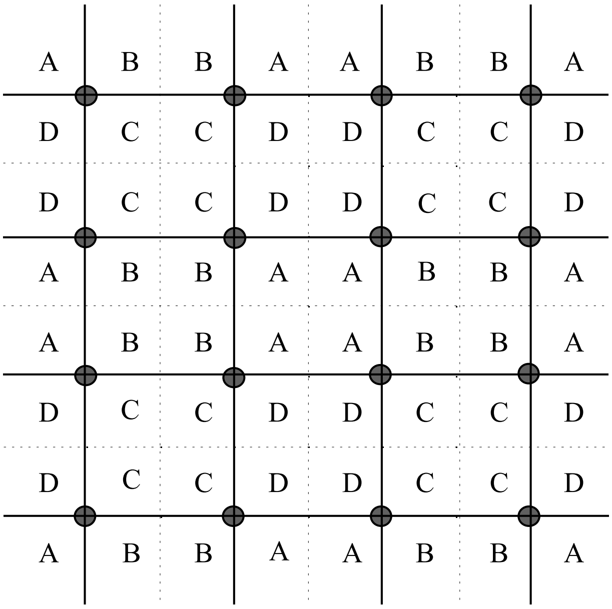


Fig.1. Rectangular cell pattern with 90° sectors.

This description is actually more specific to BWA at millimeter-wave frequencies, where the beamwidth of subscriber antennas can be as small as 3° – 5°. At microwave frequencies below 11 GHz, which are the main topic of this paper, subscriber antenna directivity is much lower, and omni-directional antennas are actually needed for mobile reception.

The channel bandwidth in BWA differs from region to region. In Europe and other countries which follow the CEPT channeling, the channel spacing is of the form $112/2^n$ MHz, where *n* is an integer. The typical values of the channel spacing in this region are 7 MHz and 3.5 MHz. In North America, the channel spacing is of the form $80/2^n$ MHz, and the typical values are 10 MHz and 5 MHz.

2.2. Channel Characteristics

For an accurate characterization of wireless channels, we need to consider the path loss (including shadowing), multipath delay spread, fading characteristics, Doppler spread, as well as adjacent channel and co-channel interferences. The path loss, which is terrain dependent, only impacts the link budget, and will not be considered here. Also, the Doppler spread in BWA networks is very small, particularly for fixed and nomadic applications. Therefore, what truly characterize BWA systems based on non-line-of-sight (NLOS) propagation are the multipath delay spread and the fading characteristics.

Channel dispersion (multipath delay spread) actually depends on the cell size, the terrain and the antennas used. In some cases, it is limited to a few µs, but in some networks with large cell sizes, the channel dispersion may exceed 10 or even 20 µs. To assess the performance of different transmission techniques, the IEEE 802.16 group used the channel models developed by Stanford University, known as the Stanford University Interim (SUI) channel models [3]. The following table gives the channel dispersion parameters of these models:

Model	Tap 1	Tap 2	Tap 3	*rms* delay (µs)
SUI 1	0	0.4	0.9	0.111
	0	- 15	- 20	
SUI 2	0	0.4	1.1	0.202
	0	- 12	- 15	
SUI 3	0	0.4	0.9	0.264
	0	- 5	- 10	
SUI 4	0	1.5	4	1.257
	0	- 4	- 8	
SUI 5	0	4	10	2.842
	0	- 5	- 10	
SUI 6	0	14	20	5.240
	0	- 10	- 14	

Table 1. Multipath delays characteristics of SUI channel models.

In all of these models, propagation is assumed along three paths, and for each channel tap (path), the first row gives the delay in µs and the second raw gives the attenuation relative to the first path in dB. The last column indicates the *rms* value of the channel delay in µs. The first three models correspond to small channel dispersion, the maximum delay being on the order of 1 µs. In contrast, the last three models have significant channel dispersion ranging from 4 to 20 µs and the one with the highest frequency selectivity of these models is SUI 4, in which the second path is only attenuated by 4 dB and the third path is attenuated by 8 dB with respect to the first path. The tap parameters in Table I are averaged signal values, and the instantaneous values follow a Rice distribution. The key parameter of this distribution is the K–Factor, defined as the ratio of the fixed signal component power to the power of its scattered components. The K-Factor decreases as the distance increases and the antenna directivity decreases, and in many realistic situations, it takes values close to 0. The limiting case of K-Factor = 0 corresponds to Rayleigh fading.

2.3. Discussion on Channel Equalization

The channel dispersion in SUI 4 to SUI 6 covers a large number of symbol durations, particularly for wideband channels. On a 7 MHz channel, the symbol rate is 5.6 Mbaud and the symbol period is 178 ns. On this channel, the impulse response of the SUI 5 model spans 56 symbol periods. If we next consider a 28 MHz channel, the symbol rate will be 4 times higher, and the same impulse response will span 224 symbol periods. Furthermore, these numbers are doubled with the SUI 6 model whose impulse response spans 20 µs.

These figures indicate that the channel dispersions encountered in BWA may be very large compared to the symbol period. For this reason, the transmission technique used must be capable of compensating for long impulse responses (spanning hundreds of symbol periods).

The conventional approach to digital communications over dispersive channels is single-carrier transmission (SCT) with time-domain equalization (TDE) [4]. Simple linear equalizers, decision-feedback equalizers, and maximum-likelihood sequence estimators have been used for decades in voice-band modems, digital microwave radio links, mobile cellular systems and other applications. But it turns out that time-domain equalizers fail to work efficiently when the channel impulse response is excessively large.

The limitation of SCT/TDE can be explained using simple heuristic arguments about equalizer convergence and tracking of channel variations. Indeed, under the minimum mean-square error (MMSE) criterion, the optimum coefficients of a linear transversal equalizer are the solution of the matrix equation

$$C = A^{-1}V \tag{1}$$

where A is the autocorrelation matrix of the input signal vector X_k, and V is the cross-correlation of the input signal vector X with the transmitted symbol a_k [4]. The conventional least mean squares algorithm for coefficient adaptation at time k is

$$C_{k+1} = C_k - \alpha X_k^* e_k \tag{2}$$

where α is the step-size parameter which controls convergence, and e_k is the equalizer output error at time k. Eqn. (2) clearly shows that the equalizer coefficients do not converge independently of each other. Not only their adaptation is driven by the same error signal e_k, but also the components of the vector X_k are correlated. In the steady state, the coefficients fluctuate around their optimum values and the resulting algorithm self-noise increases with the number of coefficients. To keep this noise below an acceptable limit, the step-size parameter must be decreased as the number of coefficients is increased. Equalization of channels with a long impulse response requires a large number of coefficients in the equalizer, and the small step size imposed by the algorithm self-noise is incompatible with the convergence and tracking requirements of the algorithm.

3. IEEE 802.16 TECHNOLOGIES

One of the main technologies for handling long impulse responses is orthogonal frequency-division multiplexing (OFDM), which was previously adopted in the IEEE 802.11a specifications for wireless local area networks at 5 GHz [5]. This technology was also adopted in the IEEE 802.16 specifications. In addition to the OFDM-based physical (PHY) layer, the IEEE 802.16 specifications also include a single-carrier PHY layer, which when combined with frequency-domain equalization (SCT/FDE) [6], can equally compensate for long impulse response channels. Furthermore, the OFDM-based PHY comprises an OFDM/TDMA mode and an orthogonal frequency-division multiple access (OFDMA) [7] mode, which means that the IEEE 802.16 specifications actually include three different transmission and multiple access techniques. However, only the OFDM mode of the IEEE 802.16 specifications is used by the WiMax Forum for fixed services, although the IEEE 802.16e specifications used for mobile services are limited to OFDMA.

3.1. OFDM/TDMA

OFDM is a multi-carrier transmission technique, where the spacing between two adjacent carriers is identical to the inverse of the symbol period. The basic idea behind this technique is to split the channel bandwidth into a large number of sub-channels such that the channel frequency response is essentially flat over the individual sub-channels. This is performed using an inverse Discrete Fourier Transform (DFT) at the transmitter and a forward DFT at the receiver. More specifically, the transmitter of an OFDM system with N carriers includes a serial-to-parallel (S/P) converter, an inverse DFT operator of size N, and a parallel-to-serial (P/S) converter that serializes the DFT output before sending it to subsequent filtering, modulation and frequency up-conversion stages. The S/P converter partitions the incoming data stream into N-symbol blocks of $T_{OFDM} = NT_S$ seconds, where T_S is the symbol period of the original serial data stream.

Suppose $(a_1, a_2, \ldots\ldots, a_N)$ designates one of these blocks. This block is passed to the input of the inverse DFT operator, whose corresponding output block is denoted $(b_1, b_2, \ldots\ldots, b_N)$. Since the inverse DFT is a periodic transform which shifts the discrete signal from the frequency domain to the time domain, the input symbols are actually transmitted at N different frequencies spaced by $1/T_{OFDM}$ *Hz*. The output blocks are serialized, and a length-L cyclic prefix is added to each of them, to form length-(N+L) blocks of the form $(b_{N-L+1}, \ldots\ldots, b_N , b_1, b_2, \ldots\ldots, b_N)$. Provided that the cyclic prefix length L is larger than the channel impulse response length, successive DFT blocks do not interfere with each other and furthermore, the linear convolution of the channel looks like a circular convolution after removal of the cyclic prefix at the receiver [6]. After the inverse DFT and cyclic prefix insertion, an OFDM transmitter includes the same operations as single-carrier transmitters, i.e., filtering, modulation, frequency up-conversion and other.

On the receiver side, the received signal is first converted back to baseband, demodulated and sampled. Then, the receiver comprises the inverse operations of those used at the transmitter. Specifically, the cyclic prefix is removed and the resulting signal blocks are passed to an N-point forward DFT operator. Suppose that the DFT output corresponding to the symbol block $(a_1, a_2, \ldots\ldots, a_N)$ is denoted $(x_1, x_2, \ldots\ldots, x_N)$. Then, we have

$$x_n = H_n a_n + noise, \tag{3}$$

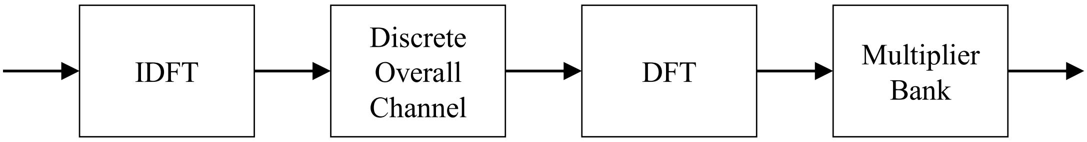
where H_n designates the channel frequency response at the nth carrier frequency. Each symbol of the block is clearly affected by the channel transfer function at the carrier frequency at which it is transmitted. Compensation of the channel response requires a complex multiplier bank after the forward DFT operator, where each multiplier coefficient is the inverse of the corresponding value of the channel transfer function. This operation equalizes the channel and restores the phase and amplitude of each transmitted symbol, but symbols transmitted at deeply faded carrier frequencies suffer an excessive error probability. Therefore, OFDM resorts to error correction coding and interleaving in order to protect these symbols.

The two important parameters of an OFDM system are the number of carriers and the length of the cyclic prefix. The cyclic prefix represents overhead, and its ratio to the number of carriers represents the loss in spectral efficiency. In the IEEE 802.16 specifications, the number of carriers is 256, and the prefix can have up to 64 samples (a quarter of an OFDM symbol). On a 7-MHz channel, a 64-sample prefix can absorb 64x178 = 11.39 µs of channel dispersion, which is sufficient for all models except SUI 6. For the SUI 1 – SUI 3 models in which the channel dispersion does not exceed 1.1 µs, the prefix size can be reduced to 8 samples, reducing the corresponding overhead from 25% to approximately 3%.

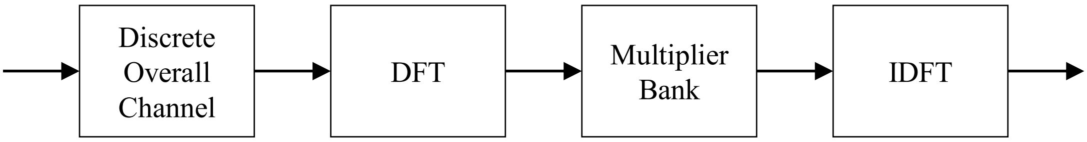
3.2. Single-Carrier Transmission (SCT)

When OFDM was first proposed for Digital Audio and Video Broadcasting (DAB, DVB) Applications in the late 1980s and the early 1990s, it was generally assumed that SCT does not give adequate performance on difficult radio channels, particularly for mobile reception. Then, in the 1993-1995 period, H. Sari et al. published a number of articles (see, e.g., [6]), in which it was indicated that the limitation of SCT was the result of constraining this technique to use a time-domain equalizer (TDE). It was shown in these papers that an SCT/FDE system resembles and achieves the performance of an OFDM system, while avoiding its well-known problems, which are its high peak-to-average power ratio (PAPR) and strong sensitivity to the local oscillator phase noise.

A schematic block diagram of the basic transmitter and receiver functions in OFDM and SCT/FDE is given in *Fig. 2.* As can be seen in this figure, there is a strong resemblance between an OFDM system and an SCT/FDE system. Both systems are frequency-domain techniques and use the forward and inverse DFT operators. But whereas one of these operators is at the transmitter and one at the receiver in OFDM, both of them are at the receiver side in SCT/FDE. In both techniques, channel estimation at the receiver is made in the frequency domain, and since the channel response at different frequencies can be estimated independently of each other, these techniques do not have the limitations of SCT/TDE that were described in the previous section.



(a) OFDM



(b) SCT/FDE

Fig. 2. Transmit and receive block diagrams in OFDM and SCT/FDE.

To view that SCT/FDE avoids the difficulty of SCT/TDE in compensating for very long impulse response channels, let ($r_1, r_2, \ldots\ldots, r_N$) denote the DFT input in *Fig. 2.b* and let ($X_1, X_2, \ldots\ldots, X_N$) denote its output. The optimum values of the complex multiplier bank coefficients ($G_1, G_2, \ldots\ldots, G_N$) are given by

$$G_n = \frac{1}{H_n}, n = 1,2,\ldots\ldots,N. \qquad (4)$$

That is, each coefficient is the inverse of the channel transfer function at the corresponding frequency. After this multiplier stage, the signal block is passed to the DFT operator that converts the signal back to the time domain. The time-domain signal samples are sent to a threshold detector to make symbol decisions. Since the channel transfer function can be easily identified at any frequency independently of other frequencies, the equalizer coefficients in SCT/FDE can be set independently of each other. As a result, the number of coefficients can be very large without prohibitively increasing self-noise. This analysis suggests that the real issue for long impulse response channels is not OFDM vs. SCT, but instead frequency-domain equalization vs. time-domain equalization.

The IEEE 802.16 group did not specifically indicate that SCT must use an FDE, because standards do not specify how to implement a receiver and what kind of equalizer to use. But only when it uses FDE, SCT becomes an alternative technique to OFDM, and the frame adopted in the specifications allows using this type of receiver.

3.3. OFDMA

In the OFDM mode of IEEE 802.16 specifications, users access the channel in TDMA mode. In this scheme, the BS assigns time slots to different users, and a time slot is an integer multiple of an OFDM symbol. The third transmission mode included in the IEEE 802.16 specifications is orthogonal frequency-division multiple access (OFDMA) [7]. In this technique, the N symbols per DFT block (or equivalently, the N carriers) are not all assigned to the same user, but instead they are partitioned into M subsets of N/M symbols, and resource assignment is performed subset by subset. This means that resources can be allocated to M users during the same OFDM symbol period.

OFDMA has several interesting features with respect to OFDM/TDMA. First, it reduces the granularity of the bursts allocated to different users thereby increasing the efficiency of the MAC protocol. Next, it increases the cell range in the upstream direction by concentrating the power available from the transmit amplifier on a subset of carriers. (Every division by a factor of 2 of the number of carriers used per subscriber is equivalent to increasing the transmit amplifier power by 3 dB.) This means that an OFDMA system based on splitting the total number of carriers N by 16 and allocating a single subset to users will increase the cell coverage by as much as 12 dB. OFDMA can also increase the cell range in the downstream direction by allocating unequal transmit powers to different carrier subsets. Indeed, by allocating more power to carrier subsets assigned to distant users and less power to carrier subsets assigned to nearby users, OFDMA makes a better use of the total transmit power and increases the cell range with respect to OFDM/TDMA.

Note that OFDMA was originally proposed [7] for the upstream channel in cable networks, which suffers from narrowband interference. In this environment, OFDMA is indeed the most robust multiple access technique, because it can discard the carrier frequencies affected by interference and uses the other frequencies which do not suffer any degradation. In contrast, CDMA and TDMA only offer a limited protection given by the processing gain (the ratio of the multiplexed signal bandwidth to the bandwidth of the individual user signals in the single-user case), and both systems break when the interference power exceeds some threshold.

4. OTHER ADVANCED TECHNOLOGIES

The transmission techniques presented in the previous section can efficiently compensate for the channel dispersion encountered in BWA systems, but diversity techniques are also needed to compensate for the fading which characterizes the tap values in the channel models. Receive diversity is very common in wireless systems, and this does not need to be specified as it is a pure receiver implementation issue. This technique is easily implemented in the uplink, but it is undesirable to use it in the downlink, as this would significantly increase the complexity of user terminals. For the downlink, the IEEE 802.16 specifications include

Alamouti's transmit diversity [8], which leads to the same diversity gain as maximum-ratio combining (MRC) in receive diversity. Note however that the transmit power in Alamouti's scheme is equally divided between the two transmit antennas and has therefore an inherent loss of 3 dB compared to MRC-type receive diversity. The IEEE 802.16e specifications for mobile services also include optional space/time codes (STC) for implementing multi-input/multi-output (MIMO) techniques with 2, 3, and 4 transmit and receive antennas, respectively, which can trade off between diversity and throughput [9].

When the two antennas are uncorrelated, diversity techniques significantly improve bit error rate (BER) performance. Using the SUI-3 channel, this is illustrated in Fig. 3 for the IEEE 802.16 OFDM specifications with an overall (Reed-Solomon and convolutional) code rate of 3/4 and 64-QAM signal constellation. For the receive diversity case (MRC) and the transmit diversity case (STC), the figure shows two different curves. The curve labeled "*Theory"* corresponds to ideal performance (with perfect knowledge of the channel), and the curve without this label takes into account channel estimation errors. We can see that in the absence of channel estimation errors the improvement of the carrier-to-noise ratio (C/N) at the BER of 10^{-4} is on the order of 10 dB for MRC and of 7 dB for STC. Next, we can see that the C/N degradation due to channel estimation errors is on the order of 0.5 dB with MRC and of 1 dB with STC. The higher C/N degradation in the case of STC is not surprising, because channel estimation errors lead to interference between the two transmit signals in this case.

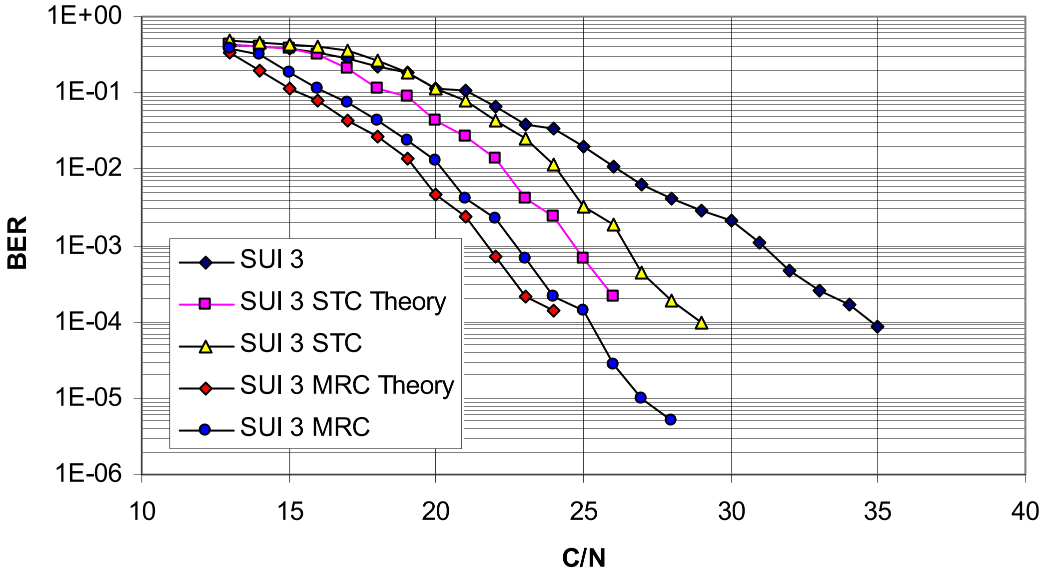


Fig. 3. BER performance of 64-QAM with Receive Diversity (MRC) and Alamouti's Transmit Diversity (STC) on the SUI-3 Channel.

Next, using the same channel model, we investigated the performance improvement that can be achieved using OFDMA on the uplink. The results are shown in Fig. 4, where the SC parameter designates the number of subchannels assigned to the user at hand. The total number of carriers here is 256 and each subchannel is composed of 16 carriers. SC = 1 means that only one subchannel is assigned to the user; in other words, the user signal occupies only (1/16)th of the channel bandwidth. To the other extreme, SC = 16 means that all of the subchannels are assigned to the same user, i.e., the user signal occupies the entire channel bandwidth, exactly as in OFDM or SCT. As in Fig. 3, the modulation scheme used in these simulations is 64-QAM, and aggregate coding rate of the Reed-Solomon and convolutional code is 3/4.

Note that each division by a factor of two of the transmitted signal bandwidth gains 3 dB in terms of C/N, where C is the carrier power and N is the noise power in the full channel bandwidth. Therefore, on a Gaussian channel, SC =1 gains as much as 12 dB with respect to SC = 16. But the net gain on a fading channel is smaller than this number, because some amount of frequency diversity is lost as the SC parameter is decreased. This is particularly visible in Fig. 4 for SC values below 8.

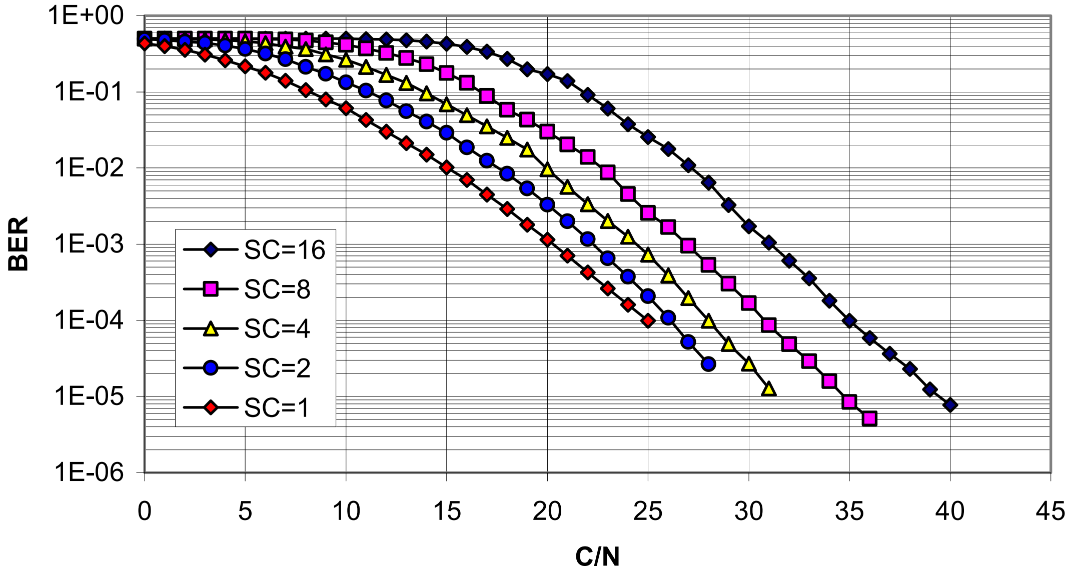


Fig. 4. BER performance of OFDMA on SUI-3 with different numbers of subchannels.

5. CONCLUSIONS

In this paper, we have discussed the multipath propagation problems encountered in BWA at microwave frequencies between 2 and 11 GHz and reviewed the basic transmission technologies adopted in the IEEE 802.16 and IEEE 802.16e standards to compensate for them. We indicated that the large channel dispersions encountered in these networks are difficult to compensate using conventional time-domain equalizers, and we gave heuristic arguments that the real issue in these systems is not OFDM vs. single-carrier transmission, but instead frequency-domain vs. time-domain equalization and signal processing. For fixed BWA applications, the industry forum WiMax has aligned itself with the OFDM/TDMA mode of the IEEE 802.16 specifications, but for mobile services, it will likely use the OFDMA mode of the IEEE 802.16e specifications. After discussing the transmission technologies that are intended to compensate for the channel frequency selectivity, we briefly described the diversity and space-time coding techniques used to compensate for fading. With all of these advanced transmission techniques incorporated in the standard and the availability of low-cost microwave radio technologies today, BWA is expected to become a competitive technology in the near future.

REFERENCES

[1] IEEE 802.16-REVd/D5-2004, “Draft IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed Broadband Wireless Access Systems,” May 2004.
[2] IEEE P802.16e/D5, “Draft IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems,” IEEE 802.16, September 2004.

[3] IEEE 802.16a-03/01, “Channel Models for Fixed Wireless Applications,” IEEE 802.16, June 2003.

[4] J.G. Proakis, "Digital Communications" (Third Edition), McGraw Hill, New York, 1995.

[5] P802.11a/D6.0, "LAN/MAN Specific Requirements – Part 2: Wireless MAC and PHY Specifications – High Speed Physical Layer in the 5 GHz Band," IEEE 802.11, May 1999.

[6] H. Sari, G. Karam, and I. Jeanclaude, "Transmission Techniques for Digital Terrestrial TV Broadcasting,"IEEE Communications Magazine, vol. 33, pp. 100-109, Febr. 1995.

[7] H. Sari and G. Karam, "Orthogonal Frequency-Division Multiple Access and its Application to CATV Networks," European Transactions on Telecommunications (ETT), vol. 9, no. 6, pp. 507-516, November – December 1998.

[8] S. M. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications," IEEE J. Select. Areas Commun., vol. 16, no. 8, pp. 1451 – 1458, October 1998 .

[9] V. Tarokh, N. Seshadri, and R. Calderbank, "Space-Time Codes for High Data Rate Wireless Communications: Performance Criterion and Code Construction," IEEE Trans. Information Theory, vol. 44, no. 2, pp. 744 – 765, March 1998 .