Broadband Wireless Internet Forum White Paper

VOFDM Broadband Wireless Transmission and Its Advantages over Single Carrier Modulation

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ABSTRACT

In this white paper we describe a coding, modulation, and spatial processing technique for fixed broadband wireless Internet access applications and provide examples of its performance. This technique is built on Orthogonal Frequency Division Multiplexing (OFDM) and is known as Vector OFDM (VOFDM). We compare VOFDM with conventional Single Carrier Modulation (SCM), and show that for the upstream link, it provides a substantial performance improvement over SCM. In the downlink, VOFDM is capable of operating with a time-varying channel at 1 Hz. In this channel, SCM becomes inoperable. In addition, for VOFDM, spatial diversity provides a 15 dB advantage in going from a 1 TX x 1 RX system to a 2 TX x 1 RX system, a further 3 dB advantage with a 1 TX x 2 RX system, and a further 12 dB advantage with a 2 TX x 2 RX system. We also discuss phase noise, power amplifier back-off due to peak-to-average power limitations, timing and frequency offset, and the implications of receive diversity on spectral efficiency.

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1 Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation technique whereby the digital message stream is divided into parallel streams and each stream is carried at a different frequency, modulating an orthogonal signal set. OFDM employs coding both in time and across different frequencies in order to exploit diversity in the time and frequency domains. As a result, OFDM can mitigate against random and burst noise, flat as well as frequency selective fading, and co-channel interference. Vector OFDM (VOFDM) combines OFDM with spatial processing so that diversity in time, frequency, and space are exploited. This paper provides a description of VOFDM and its advantages over Single Carrier Modulation (SCM) systems. In this introductory section, a summary will be provided. A detailed discussion of the subject is supplied in the remainder of this paper.

1.1 Advantages of VOFDM

VOFDM has advantages both in the upstream (Time Division Multiple Access, TDMA) and the downstream (Time Division Multiplexing) directions in a point-to-multipoint system. The subscriber units are always in listening mode, or in other words the downstream transmission is being continuously demodulated. Whereas, the subscriber units transmit only when they have data to transmit and are given a time slot by the base station during which to transmit. Thus, the downstream direction operates in continuous mode whereas the upstream direction operates in burst mode.

VOFDM solves the *upstream problem*. It enables *robust burst-mode demodulation* even in severe time-varying and/or delay spread environments. In addition, VOFDM makes *higher spectral efficiency* possible in the upstream. An SCM system with a single antenna employing the same transmission overhead as VOFDM results in error floors, while VOFDM operates satisfactorily. The performance improvement achieved with VOFDM is about 3-9 dB with dual antennas[1].

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[1] In this paper, the performance gain of VOFDM against SCM is defined as the reduction in Signal-to-Noise Ratio at a Codeword Error Rate of 10^{-4}. A codeword corresponds to a VOFDM burst.

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In the *downstream* direction, VOFDM is capable of operating in *high delay spread and time-varying environments*. Furthermore, VOFDM provides *dual antenna capability at lower complexity*. The dual antenna capability makes *interference cancellation* possible, thereby increasing system robustness to narrowband and wideband interference. Simulations indicate VOFDM can easily operate in a 1 Hz time-varying channel, while SCM cannot.

1.2 Limitations of VOFDM

Two limitations of OFDM are often asserted. The first is *power amplifier back-off*. Due to the inevitable nonlinearities of transmitter power amplifiers, a modulated signal generates out-of-band transmissions. There are restrictions imposed by the FCC and other regulatory bodies on the level of these spurious transmissions. These restrictions impose a maximum output power limitation. This output power limitation corresponds to what is known as power amplifier back-off. Power amplifier back-off is modulation dependent. Experimental data show that OFDM has at most a 0.5 to 1.5 dB disadvantage as compared to SCM in power amplifier back-off. However, it is possible to design OFDM receivers with much more than 1.5 dB sensitivity advantage in many channel or interference scenarios, and thus the overall net sensitivity gain of using OFDM versus other techniques is quite large.

The second limitation of VOFDM is increased sensitivity to *phase noise*. OFDM requires approximately 10 dB better phase noise than a corresponding SCM system. Although this discrepancy sounds significant, the associated cost in solving this problem is low and the difference is minor at microwave frequencies.

In the remainder of this paper, limitations of wireless channels are discussed in Section 2, and conventional solutions to these problems are discussed in Section 3. A brief description of VOFDM and its history are given in Section 4. The basic building blocks of VOFDM system are described in Section 5. A description of commercially available SCM systems is provided in Section 6. A detailed comparison of VOFDM and SCM systems is given in Section 7. Section 8 summarizes and concludes the paper.

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2 Wireless Channel Impairments

In a wireless system, information is transmitted through space via modulated electromagnetic waves. Consequently, two major impairments dominate. First, wireless communication involves multipath transmission that in turn causes fluctuations in amplitude, or technically what is known as *fading*. Second, the presence of unwanted transmissions at the same frequency band causes *interference.* A wireless communication system is designed to eliminate both of these effects. There are various methods for combatting fading and interference. In this paper, it is shown how and why VOFDM is superior in accomplishing these objectives, resulting in an overall higher capacity system.

As stated above, multipath transmission causes fading. In a wireless system, multipath is due to the reflection of the main beam from various objects along the main transmission path as shown in Figure 1. Each such transmission path has an associated delay, and the overall effect of all such reflections results from the combination of delayed waves. This combination occurs vectorially at the receiver, each of the constituent electromagnetic waves contributing a different phase and magnitude at each point in space. This gives rise to a standing wave pattern at each frequency between the transmit and receive antenna pair as shown on the top in Figure 2. This change in magnitude versus space is known as fading.

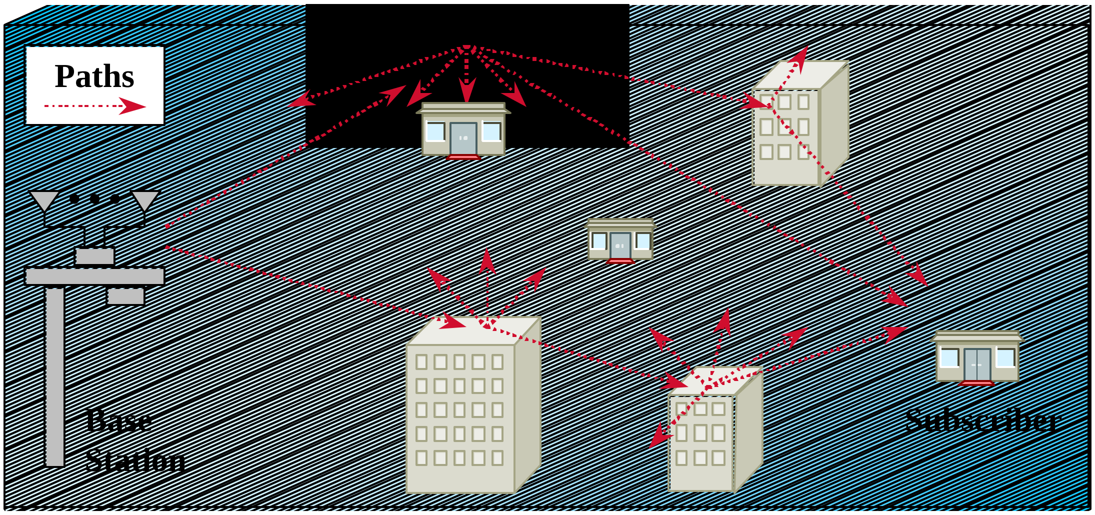

Figure 1: Wireless communication involves multipath transmission.

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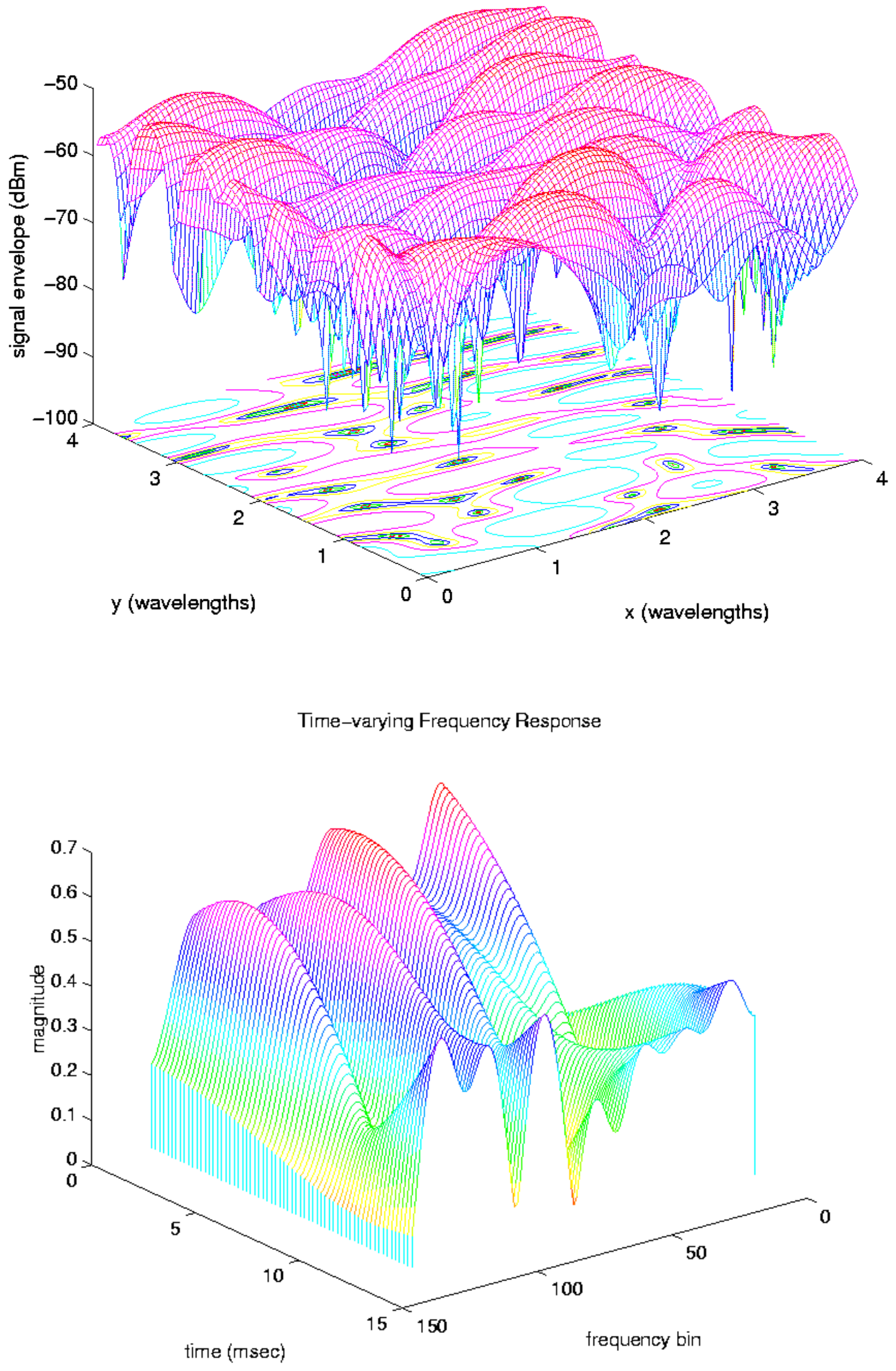

Figure 2: Effects of multipath. Top: spatial diversity, bottom: time variation.

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Fading occurs in two different types. The first is known as *flat fading.* In this case, the received signal spectrum remains a close replica of the transmitted signal spectrum except for a change in amplitude. As described above, this amplitude change of the signal spectrum varies over space because of the interference of the combined electromagnetic waves. This interference can be constructive or destructive, and as a result, the fades (changes in the received signal magnitude) due to flat fading can be very significant, 30 dB or more. Flat fading occurs when the Root Mean Square (RMS) delay spread of the channel is much smaller than the symbol period of the transmitted signal.

When the RMS delay spread of the channel is more than about 10% of the symbol period, the wireless channel alters the received signal spectrum. This is known as *frequency selective fading*. In frequency selective fading, the channel is dispersive, and the received waveform has *intersymbol interference (ISI)*. In the frequency domain, the channel response can no longer be considered “flat,” its amplitude has significant variation or its phase is not linear with frequency. In the time domain, the received symbols can no longer be identified individually. They interfere with each other since they are dispersed in time and overlap one another. In this case, the wireless system should use a signal processing technique to remove this intersymbol interference. These techniques are, in general, known as channel equalization techniques.

If the objects in the medium are not moving, the standing wave pattern is static in space. Thus, for a fixed point in space, the wireless channel is time-invariant. If, however, there is motion in the environment (although neither the transmitter nor the receiver may be moving), it alters each standing wave pattern and consequently the wireless channel is also time-varying. This time-varying nature of wireless channels makes the problem of channel equalization much more difficult as compared to wireline systems such as voiceband or subscriber loop modems.

Refer again to Figure 2. The upper portion of the figure shows the standing waves between the transmitter and receiver due to multipath, or fading. The lower portion of the figure illustrates the effect of time-varying frequency selective fading.

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In fixed, as well as mobile, cellular wireless systems, interference is a significant limiting factor. Calls in a neighboring cell employing the same channel cause *co-channel interference.* Increasing the transmitter power does not remove co-channel interference because it results in the increased interference to neighboring cells employing the same channel. In addition, there could be interference due to the existence of other services in the frequency band. For example, in the San Francisco Bay Area, analog video interference is present in virtually every MMDS channel (Multipoint Microwave Distribution System: licensed frequency band at 2.5-2.686 GHz for fixed broadband wireless access applications in the U.S.).

3 Some Solutions

The most commonly used solution to multipath fading in high data rate fixed wireless systems is careful site selection and engineering. The goal is to provide a single, unobstructed path between the transmitter and receiver. This makes it necessary to establish a Line-of-Sight (LOS) path between the transmitter and receiver antennas. This careful site selection process is by no means easy to accomplish, typically requiring high effort and cost. Highly directive antennas are often used to eliminate reflections. Directive antennas are more expensive and may be aesthetically undesirable. In addition, establishing an LOS path between the transmitter and receiver antennas is not possible at every subscriber site in a point-to-multipoint system.

Limiting link range and providing a signal strength margin can be effective against flat fading. The signal strength (or fade) margin required can be large (tens of dB). This results in a substantial loss of range and coverage. In addition, space diversity by means of multiple antennas can help solve the problem. With adequate antenna separation, when the signal received by one antenna fades, there is a good probability that the signal strength at the other antenna is still sufficiently large. This greatly reduces the amount of fade margin required. Hence two spatially separated antennas greatly increase coverage and range of a system without increasing power. For example, a smaller power amplifier at the subscriber unit can be used in conjunction with multiple antennas at the base station. In the same way, transmit diversity may be used to reduce fade margin in the downstream by using two transmit antennas at the base station.

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The conventionally employed technique against frequency selective fading is to use equalizers. Methods of equalization are well-established. Decision Feedback Equalization (DFE) is known to provide close to optimum performance once the equalization algorithm has converged or fully adapted. Furthermore, equalization algorithms with varying degrees of speed of convergence, computational complexity, and stability are well-understood. The Least Mean Squares (LMS) algorithm is computationally simple and stable, but converges slowly. The Recursive Least Squares (RLS) algorithm converges quickly but is far more complex than LMS. In addition, it has known stability problems. Both algorithms require a training sequence (blind techniques exist but are not efficient). This is especially important for packet transmission where the channel may change significantly between transmissions of different packets. As will be shown later, the complexity of DFE increases significantly with transmission rate.

In a given system, the conventional method to mitigate co-channel interference is to increase the distance between cells where the same frequency channel is used, i.e., by decreasing frequency reuse. However, reducing frequency reuse reduces capacity. For example, one can keep the total spectrum constant and increase the number of frequency channels. Then, one can increase the number of cells in the reuse pattern. Consequently, the co-channel interference of the system decreases together with system capacity.

Mitigation of narrowband interference can be achieved by spreading the signal over the frequency band. While this can be done via spread spectrum techniques, it can also be accomplished by using OFDM and coding across the frequency band. Indeed, coding and OFDM exhibit a spreading gain similar to spread spectrum techniques.

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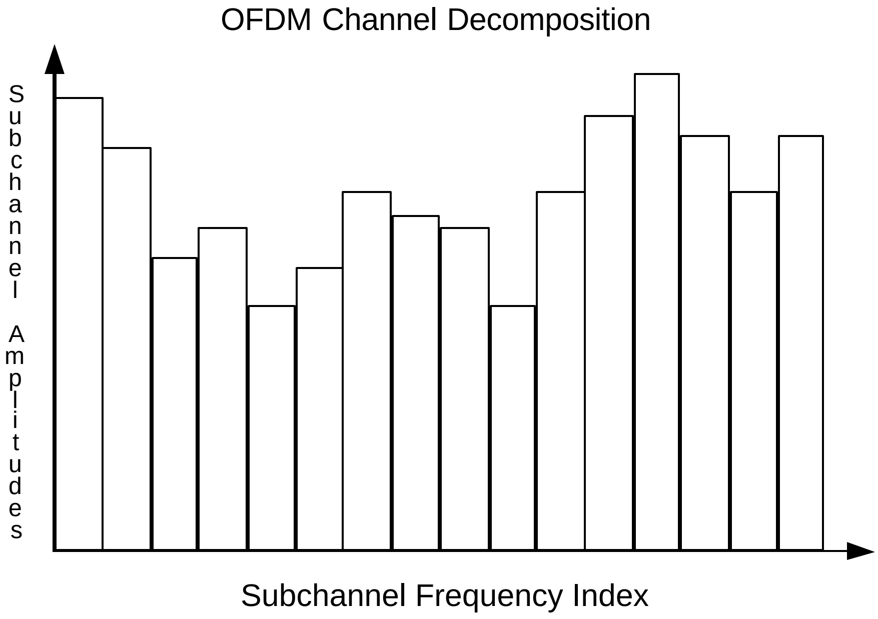

Figure 3: The OFDM concept.

4 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a method to solve the multipath problem. Although there are other techniques to solve this problem, (for example, Single Carrier Modulation (SCM) and equalization, direct sequence spreading, adaptive space-time coding solutions), OFDM has important advantages and is especially preferable at high transmission rates. OFDM is a special case of Frequency Division Multiplexing (FDM). The presence of an orthogonal transform in FDM provides implementation simplicity and spectral efficiency. OFDM decomposes the ISI channel into many ISI-free narrowband channels as illustrated in 3. Unlike single carrier techniques, in OFDM, an equalizer is not used to equalize or invert the channel.

We note that the representation in 3 is a simplification. In reality, the shape of the waveform corresponding to each subchannel frequency index is a function of the form $\sin(f_k)/f_k$ such that each waveform has its maximum at the subchannel frequency f_k and it has value zero at other subchannel frequencies. Therefore, there is overlap in frequency among these waveforms.

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OFDM was introduced in 1966 [1], [2]. Its properties were studied in the ‘60s through the ‘90s [3], [4], with some implementations appearing in the ‘80s [5]. It gained widespread interest within the context of Digital Audio Broadcast (DAB) and High Definition Television Broadcast (HDTV) in Europe, and also for Asymmetric Digital Subscriber Lines (ADSL) as a variant known as Discrete Multitone (DMT) [6]. In OFDM, because of the introduction of a guard time, known as the cyclic prefix, the time domain effect of convolution of the channel impulse response is transformed into a frequency domain product: a complex multiplication of the data symbols with the channel frequency response. This removes intersymbol interference and alleviates the need for equalizers. It is because of this property that OFDM has gained popularity in high data rate systems. However, it has additional advantages:

1. It divides the channel into narrowband, flat fading, subchannels and thus it is more resistant to frequency selective fading as compared to single carrier systems.
2. By using FFT techniques, it is computationally efficient.
3. It can be combined with coding and interleaving to recover symbols lost due to the frequency selectivity of the channel or to narrowband interference.
4. It makes efficient use of spectrum by allowing overlap.
5. Transmit diversity may be easily added without changes to the receiver system.

Furthermore, at high sampling rates, computational complexity of OFDM is lower than conventional space-time equalization techniques. This is illustrated in Figure 4 for a Vector OFDM (VOFDM) system. VOFDM will be described in the next section in detail. For the purposes of this section, its complexity is M times more than the complexity of OFDM, where M is the number of spatial dimensions. In Figure 4, the number of complex multiply-and-accumulate operations per symbol are shown on the top and the number of complex multiply-and-accumulate numbers in millions per second are shown on the bottom against the data rate in Mbps. This comparison is only for the number of operations needed to implement DFE and VOFDM, adaptation of the DFE or the channel estimation for VOFDM is not included.

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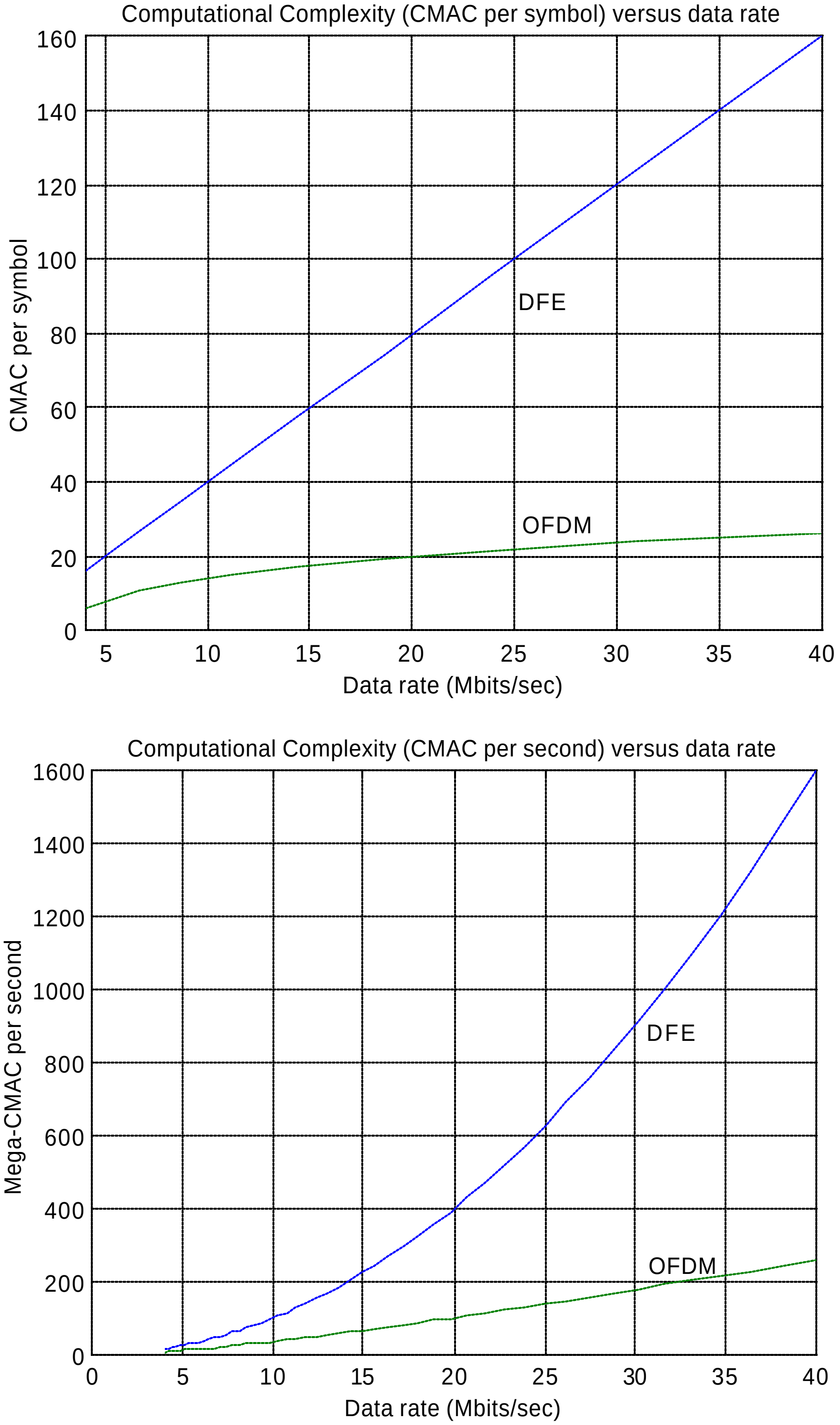

Figure 4: OFDM has lower complexity. The upper figure shows the number of complex multiply-and-accumulate operations per symbol, the lower figure shows the number of complex multiply-and-accumulate operations per second in millions. The horizontal scale is the data rate in Mbps in both figures. The delay spread is 2 µs, the burst length for OFDM is 20 µs, and the constellation size is 16 QAM.

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It can be calculated that the complexity of the VOFDM system is $2M\log(R\nu)$ per sample where M is the number of spatial dimensions, R is the sampling rate, ν is the delay spread as measured in digital-equivalent channel taps, and where log is due to the FFT operations VOFDM performs. In comparison, the complexity of the DFE system can be calculated as $4R\nu$ per sample. This is because of the inner product operation the DFE carries out. When the complexity figures are calculated per second, the complexity of the VOFDM system grows log-linearly whereas the complexity of the SCM system grows quadratically, as shown on the bottom of Figure 4. As a result, the implementation of VOFDM at high data rates becomes substantially simpler than SCM.

5 VOFDM System

OFDM was extended into an optimum spatial-temporal processing system for the dispersive spatially selective wireless channel in the '90s [7], [8]. The resulting system is known as VOFDM. An illustration of VOFDM is shown in Figure 5. VOFDM combines OFDM with spatial processing. In the combined system, OFDM is used to exploit time and frequency diversity whereas spatial processing exploits spatial diversity. The greatest benefit comes from exploiting time, frequency, and spatial diversity.

VOFDM implementation involves the following functions:

1. OFDM. The data rate and the delay spread tolerance are programmable. Cyclic and linear filtering are performed by optimal FIR filters.
2. Channel estimation. An optimum approach is used employing burst-mode training.
3. Synchronization. Both timing and frequency recovery are robust.
4. Spatial processing. In the VOFDM system, spatial processing is known as Interference Cancellation.
5. Coding. Both convolutional and Reed-Solomon coding are used, in a concatenated fashion. Optimum soft decoding is used in Viterbi decoding by incorporating measured Signal-to-Interference-plus-Noise-Ratio (SINR) weights for every transmitted bit.

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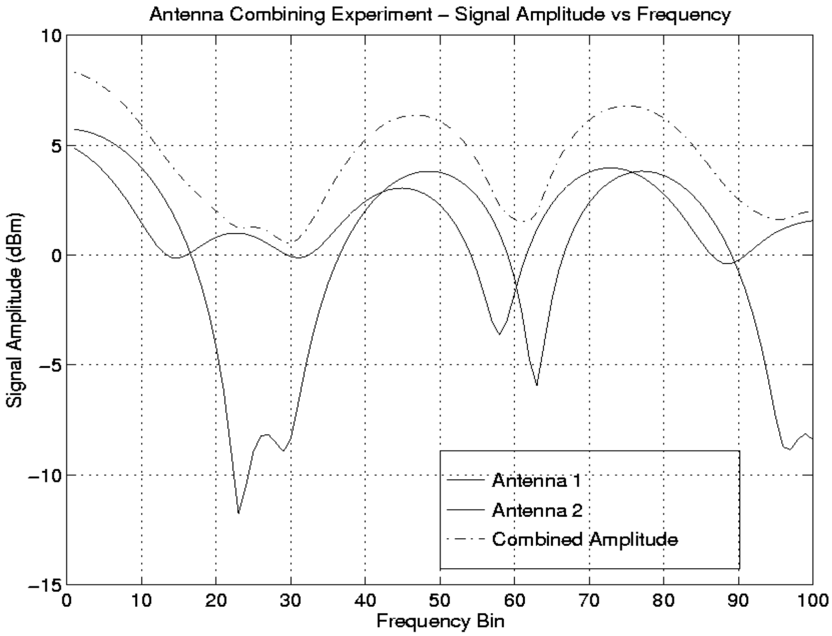

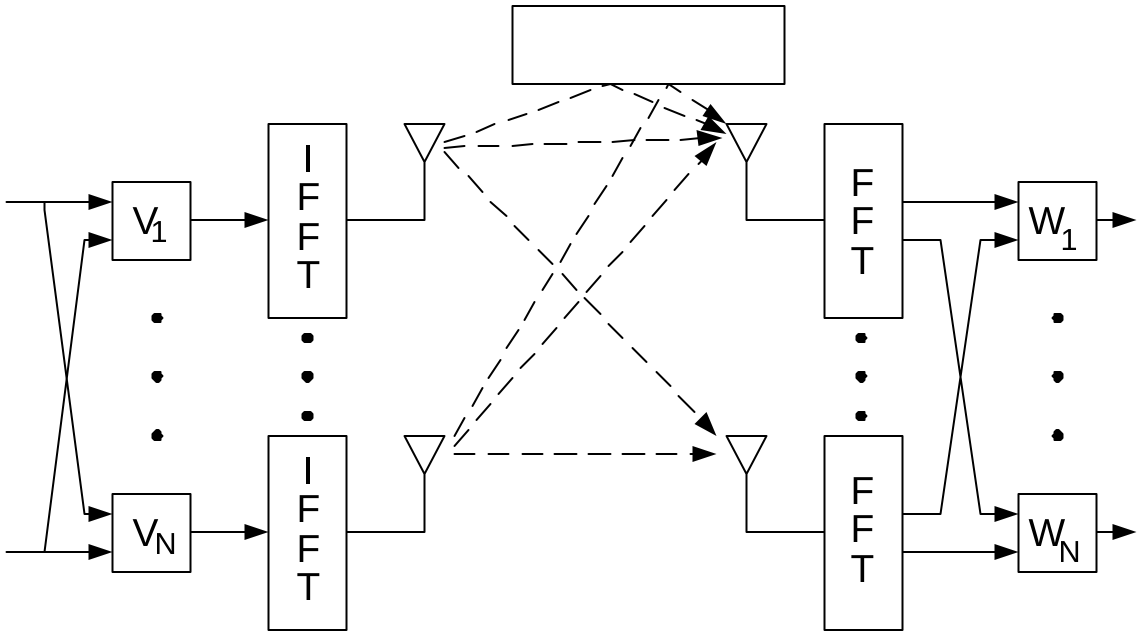

Figure 5: Space-frequency processing.

The transmit system block diagram is shown in Figure 6 and the receiver system block diagram is shown in Figure 7.

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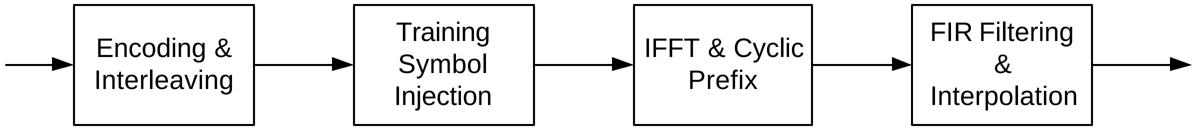

Figure 6: The transmit system block diagram.

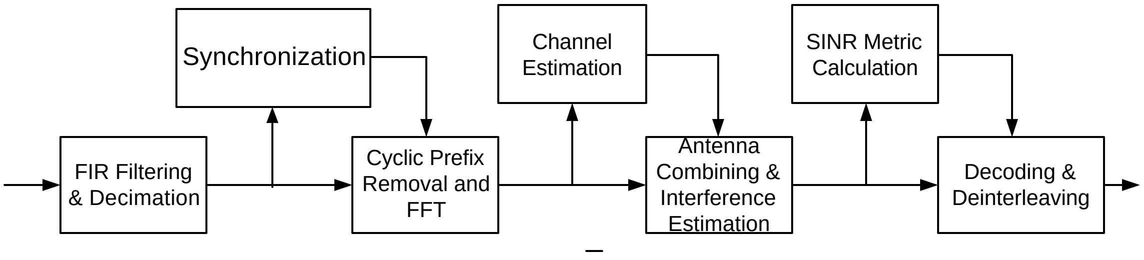

Figure 7: The receive system block diagram.

6 Commercially Available SCM Broadband Wireless Systems

The next section provides detailed performance comparisons of the VOFDM system with ideal broadband wireless SCM systems. It needs to be emphasized, however, that although the VOFDM system is available today, together with its multiple antennas (either two receive antennas, and/or, two transmit antennas) and the associated Interference Cancellation algorithms, the technical sophistication of the available low-cost broadband wireless SCM systems is highly limited. First, there are no low-cost broadband dual antenna SCM systems employing optimum space-time equalization as studied in the next section. Second, even single antenna low-cost broadband SCM systems available today are far less sophisticated than the systems presented in the next section. Consequently, the performance of today’s SCM systems will be likely worse than the idealized SCM system performance studies presented in the next section, which are already at a substantial disadvantage against VOFDM.

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7 Performance Comparisons with Single Carrier Modulation (SCM)

7.1 VOFDM Exploitation of Multipath (Upstream)

First, upstream transmissions in the burst mode are considered. The first channel considered consists of four taps spaced 1/6 μs apart for a total of ½ μs. Note that ½ μs is a small value of delay spread. We will show that VOFDM is at an advantage with this value of delay spread, and note that the values of delay spread encountered in deployment can be larger, making the advantage of VOFDM even more significant. The amplitudes of the taps are drawn from a complex Gaussian distribution with unit variance. The second channel considered has the “spike and exponential” shape of [9] which consists of a strong return (“spike”) at the lowest delay plus a set of returns whose main powers decay exponentially with delay. The model is characterized by two parameters, namely, the ratio K of the average powers in the spike and exponential components, and the decay time constant τ_0 of the exponential component. In the model, there are 16 exponential components. The factor K is -8 dB and the time constant τ_0 is 0.35 μs. There is a wide variety of MMDS channels and system design needs to be based on a target channel which represents a high percentage of all channels. With the choices described above, a large percentage of all MMDS fixed wireless channels are represented [9]. Hence, the design is based on a target channel for a robust system.

The VOFDM system employed in simulations is as described in the previous section, while the single carrier system consists of QAM modulation with an equalizer at the receiver. For the SCM system, the equalizer used is a $T/2$-spaced Feedforward Equalizer and a Decision Feedback Equalizer (refer to Figure 8) with an adaptive algorithm for training. Since the convergence speed of this equalizer is important, RLS was used in simulations. Since there is limited data available, two passes over the received data were employed to increase the probability of tap convergence. The equalizer has 31 taps in its feedforward portion and 5 taps in its feedback portion. When dual antennas are employed, two feedforward equalizers of 31 taps each are combined to feed a 5-tap feedback equalizer with decision feedback. The equalizer is trained in an explicit training mode as well as during operation, in the decision directed mode. The system overheads for VOFDM and SCM are designed equal to ensure fair comparisons. Hence, the spectral efficiencies of

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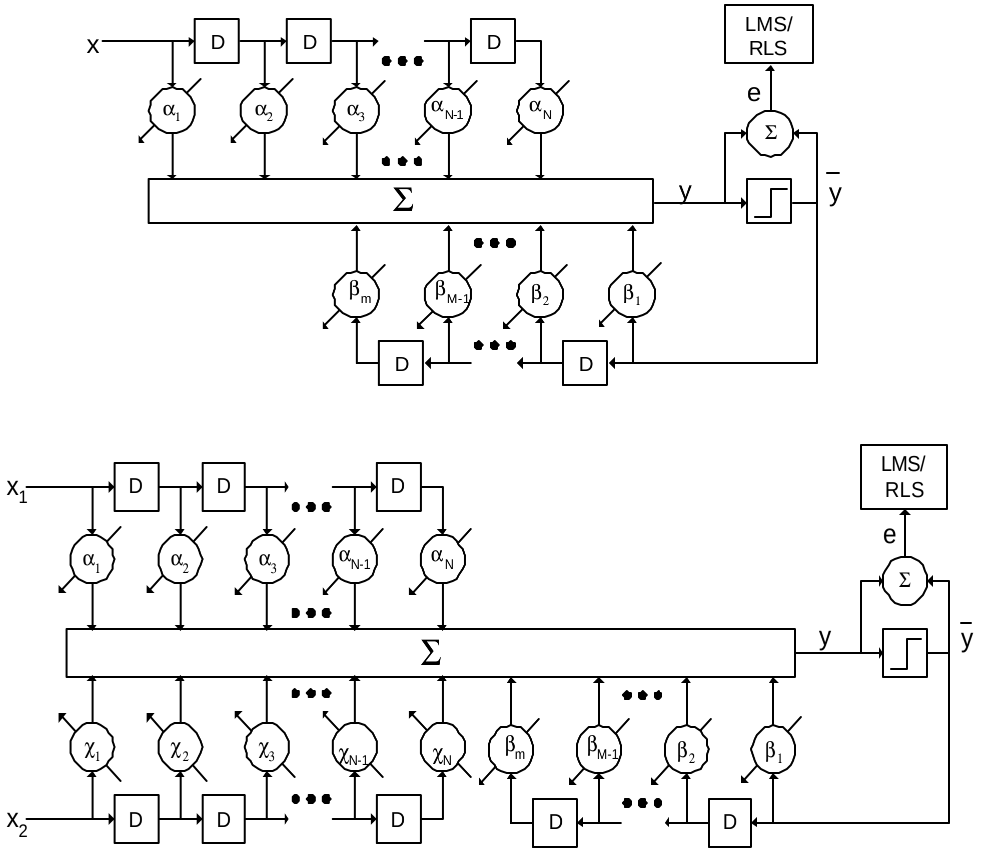

Figure 8: Decision Feedback Equalizer (DFE) used in the receiver of the single carrier system. Upper figure: single antenna system, lower figure: dual antenna system.

the two systems are equal, and the comparisons show the true performance of the two different equalization techniques in fading wireless channels. In these simulations, RLS was implemented with floating point precision. The results for SCM will be significantly inferior using 16-bit integer precision, which is a more realistic assumption for implementation.

The results are presented in Figure 9 and Figure 10 in terms of Codeword Error Rate (CER). A codeword is a concatenation of 592 bits which is treated as a single block consisting of the Reed-Solomon and convolutional coder-decoders. In both modulation constellations, VOFDM outperforms SCM in both single and dual antenna modes. The unacceptable error floors in SCM are due to equalizer convergence limitations. Observe

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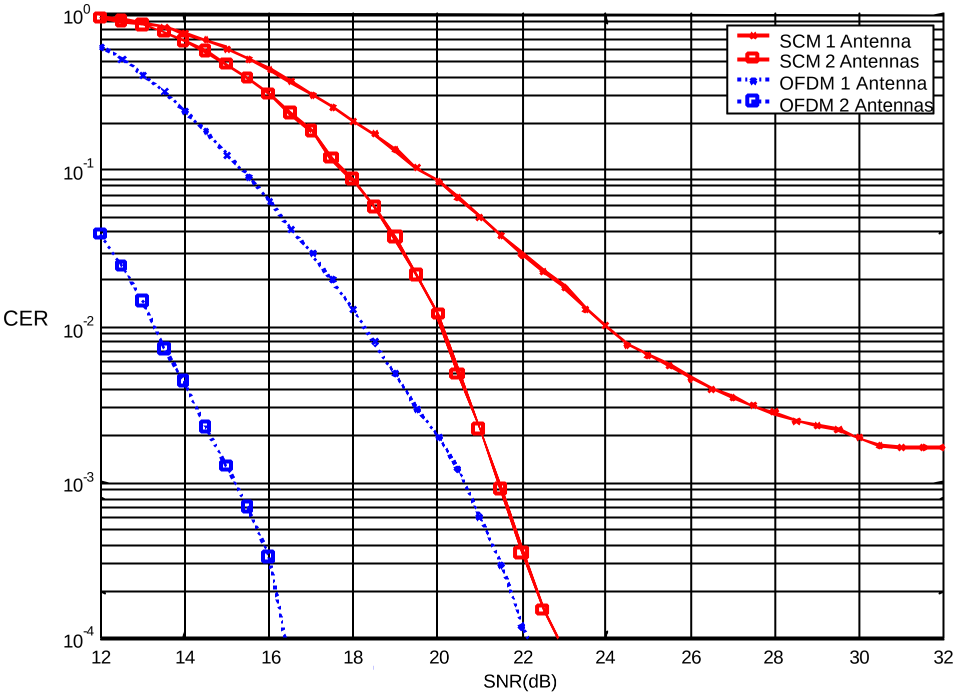

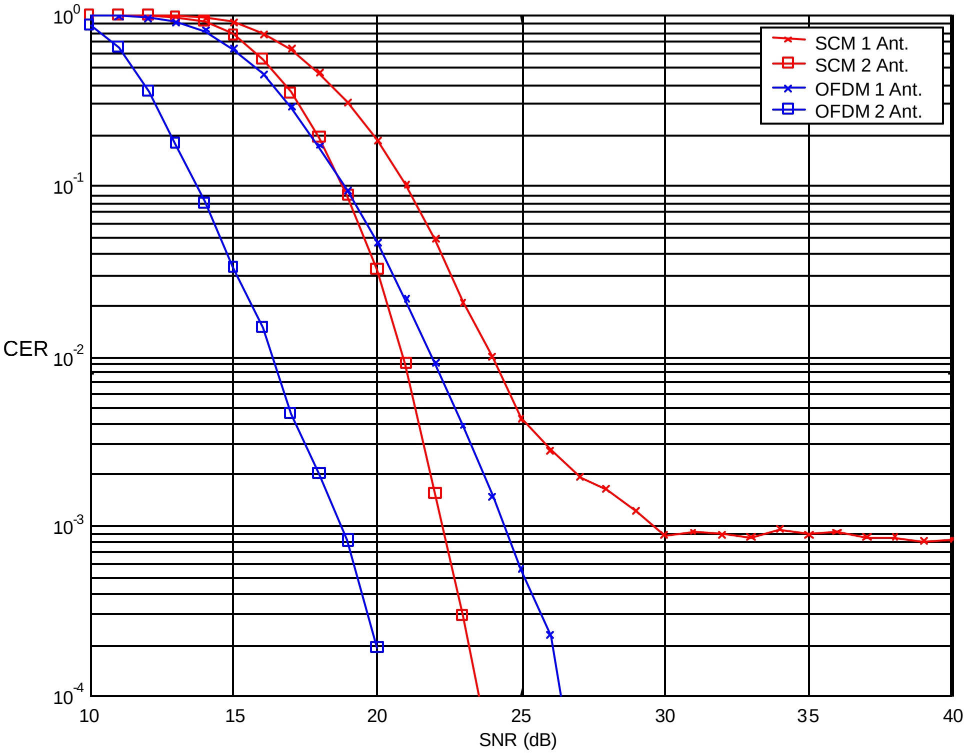

Figure 9: Upstream performance comparison of VOFDM and SCM using 16QAM. Upper figure: Channel 1,lower figure: Channel 2.

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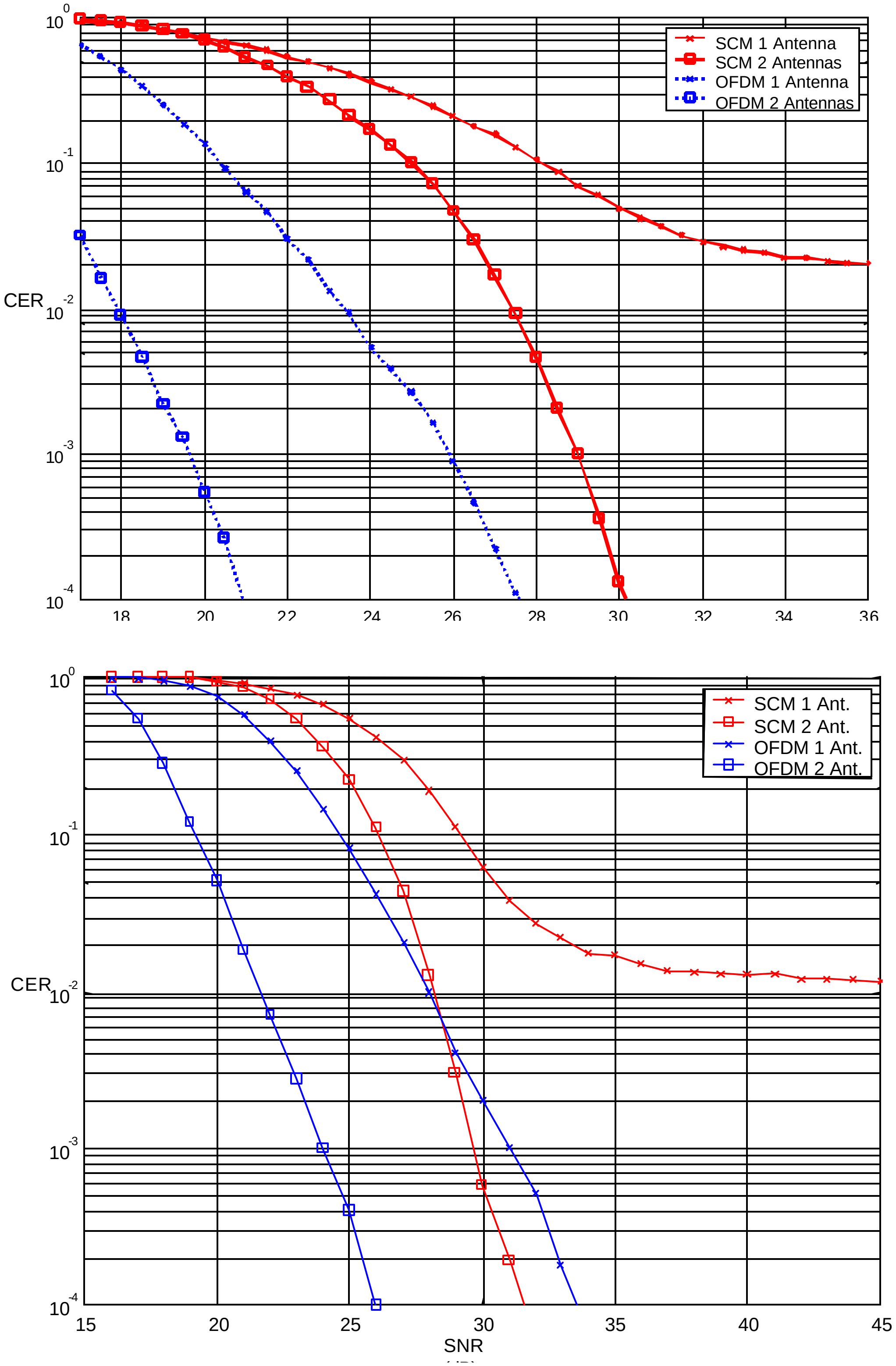

Figure 10: Upstream performance comparison of VOFDM and SCM using 64QAM. Upper figure: Channel 1, lower figure: Channel 2.

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OFDM Advantage at CER = 10^{-4}		
	Single Antenna	Dual Antenna
16 QAM Channel 1	∞	6 dB
16 QAM Channel 2	∞	3 dB
64 QAM Channel 1	∞	9 dB
64 QAM Channel 2	∞	6 dB

that the OFDM advantage at CER = 10^{-4} is as shown in the table above. To implement a dual antenna system in VOFDM, the two antenna outputs are combined using SINR combining, whereas for SCM, an optimal space-time equalizer as described above is employed. Note that VOFDM system performs SINR combining, however there are no SCM space-time equalizer products for MMDS applications in the market. Further gains are possible for VOFDM if Interference Cancellation is used. Further spatial processing gains are also possible if the simulated channels exhibit less correlation and if flat fading gains are included in the results. In general, Figure 9 and Figure 10 show that a VOFDM system provides more capacity. This is because in order to operate at the same error rate, SCM either needs more coding, or more SNR, or more Carrier-to-Interference ratio (C/I).

7.2 VOFDM and SCM in Continuous Carrier Demodulation (Downstream)

As opposed to Section 7.1 where we compared VOFDM and SCM systems in the upstream direction in the burst mode, in this subsection we compare VOFDM and SCM systems in downstream carrier demodulation. In this comparison, VOFDM and SCM system efficiencies are designed approximately equal. The simulated 6 MHz channel is a similar to Channel 2 of the previous section, with the addition of time varying components using Jakes' model at 1 Hz [10]. The SCM system equalizer employs a fully adapted equalizer using the Least Mean Squares (LMS) algorithm. The receiver employs single or dual antennas. VOFDM employs Interference Cancellation whereas SCM employs optimum space-time equalization. System parameters are as follows: FFT size is 512 symbols and 32 bytes are used for the cyclic prefix. Convolutional code rate is 2/3, and the Reed-Solomon code parameters are (n, k) = (252, 232). The equalizer uses 48 feedforward taps for each antenna and 12 feedback taps that are common.

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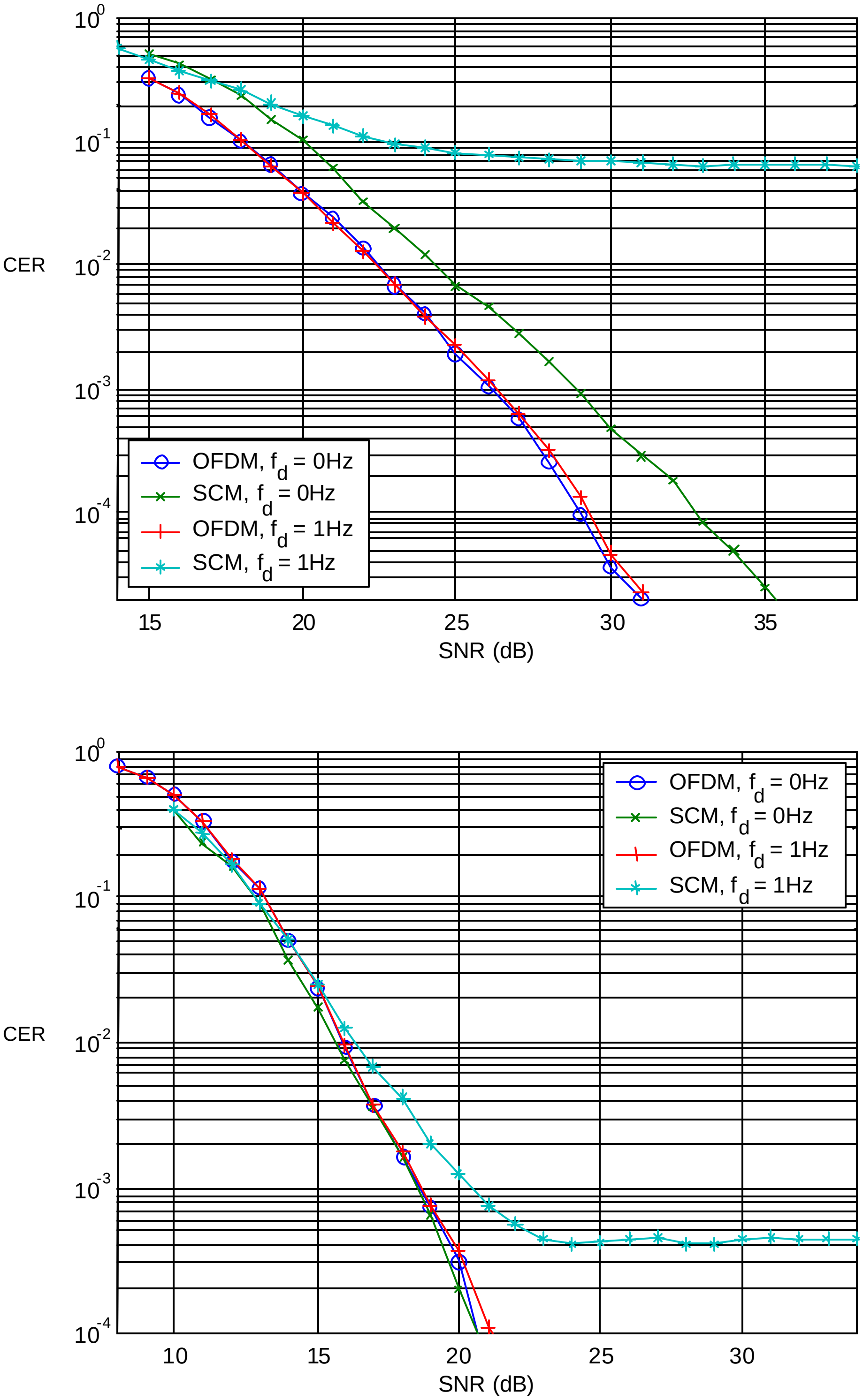

Figure 11: Downstream performance of VOFDM vs SCM with single and dual antennas on a time-varying channel using 16QAM. Upper figure: single antenna, lower figure: dual antenna.

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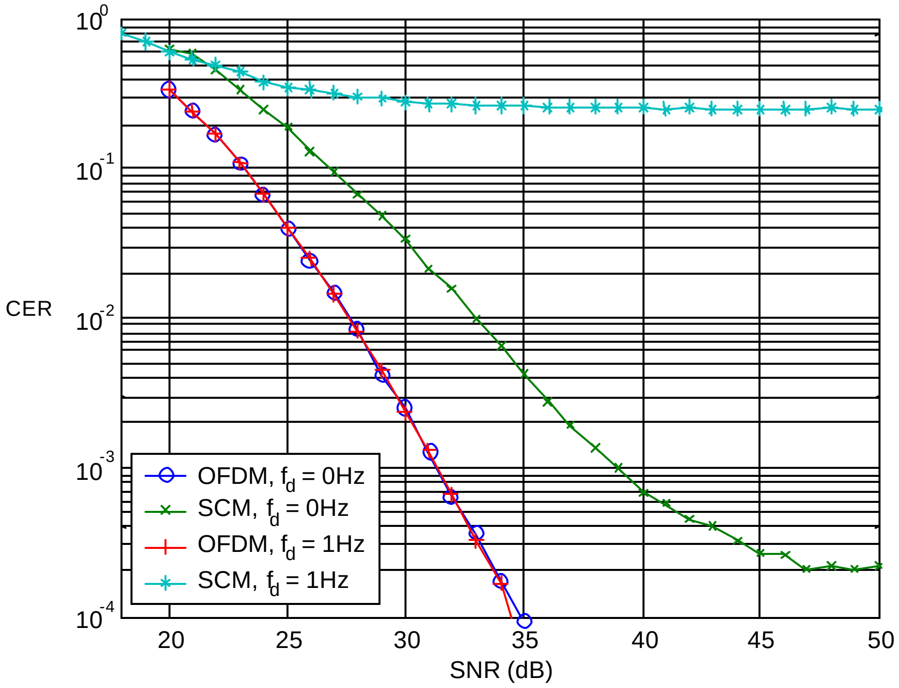

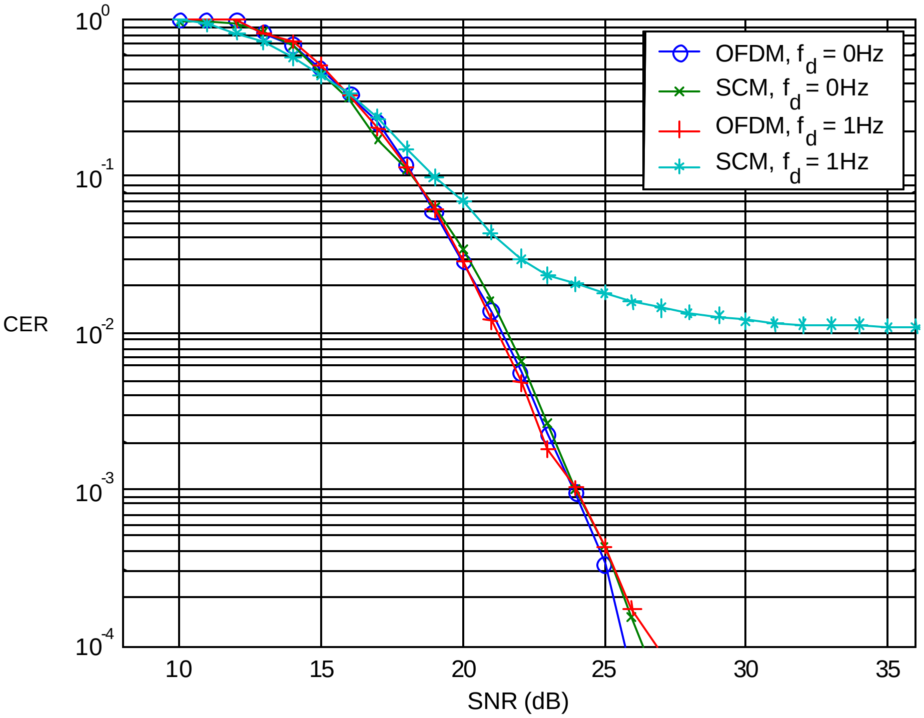

Figure 12: Downstream performance of VOFDM vs SCM with single and dual antennas on a time-varying channel using 64QAM. Upper figure: single antenna, lower figure: dual antenna.

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16QAM results are shown in Figure 11 and Figure 12 for single and dual antennas. First, note the presence of error floors with SCM systems. Error floors depend on the channel, number of antennas, Doppler frequency, and also the constellation type. Further experimentation has shown that further training does not eliminate these error floors. The OFDM system does not show error floors, and its performance does not deteriorate in the presence of the time-varying channel.

64QAM results are shown in Figure 12. While the dual antenna SCM system equals the performance of VOFDM for the time-invariant channel, it cannot adapt to the time-varying channel, whereas again, VOFDM performance does not deteriorate in the presence of the time-varying channel.

We would like to reiterate that while VOFDM system implements dual antennas, there is no known implementation of a dual antenna SCM system for MMDS broadband applications.

7.3 VOFDM Transmit Diversity

Transmit diversity can be used either on the uplink, or the downlink. Transmit diversity uses a second transmit antenna, and reduces the required fading margin by exploiting the lack of correlation between the fast fading that each transmit path encounters. Transmit diversity requires additional components beyond the standard dual-receiver configuration: a signal modifier as described below, and a second analog chain. Note that in dual receive diversity systems, the extra antenna and outdoor equipment is already available. The receiver needs no modification to support transmit diversity.

In some installation scenarios, the channel will have little delay spread. In this case, the signals from the two antennas could arrive at the receiver 180 degrees out of phase across the entire frequency band. To remedy this problem, the signal modifier is used on one transmit antenna. One implementation of the signal modifier is a pure delay element. By delaying the signal sent by the second antenna, there is no single phase of one antenna with respect to the other that will cause a fade of the entire band; instead, a series

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of notches are formed across the channel. While these notches introduce SNR degradation over the single antenna performance, complete destructive interference at all frequencies is avoided. With this delay element, the addition of a second antenna clearly improves the link budget, because the notch degradation is more than made up by the reduction in the fading margin. Other implementations of the signal modifier, besides pure delay, are possible. Another possibility is to modify the magnitude response, or a combination of the magnitude and phase responses. The design philosophy using these methods is very similar to the pure delay modifier.

Figure 13 shows the simulation results corresponding to the transmit diversity scheme. The transmit delay on the second transmit path is set to be one sample. In this simulation, the two channels consist of two complex random variables. The correlation coefficient of the random variables is a simulation parameter. For a given SNR value, the simulation consists of drawing the two random variables from a jointly normal distribution, running the VOFDM system to result in a CER. This process is repeated and average values are reported in Figure 13.

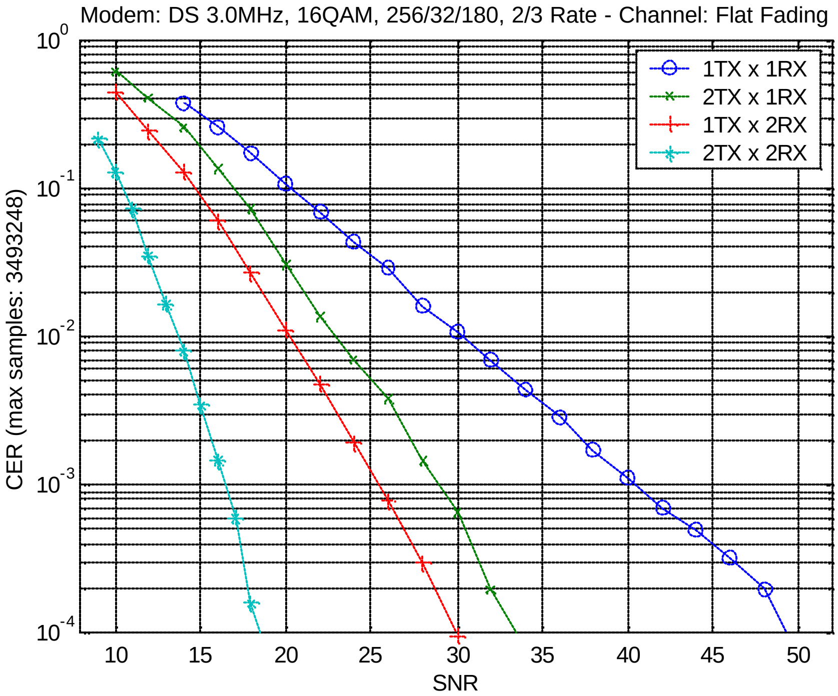

Figure 13: Simulation results for transmit diversity.

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7.4 VOFDM Receive Diversity

Receive diversity, like transmit diversity, confers a significant advantage. A system using only one antenna must employ a larger fade margin. The effect of larger fade margin is illustrated in two examples below. The first example is a macrocell scenario, in which cell size is limited by transmit power and receiver noise. The second scenario is a microcell scenario, in which capacity is limited by the mean C/I with which the cellular system can operate.

We compare a VOFDM system employing two receive antenna diversity to an SCM system employing one receive antenna. We assume that the channel gain from the headend transmitter to each Subscriber Unit (SU) receive antenna fades independently with a Rayleigh distribution. The channel for each antenna contains negligible delay spread. We use the Codeword Error Rate (CER) at the SU as a measure of performance; in general, a minimum received SNR is needed to reduce the CER to acceptable levels. Because the channel fades on each antenna, the mean SNR incorporates a fade margin. This fade margin is designed to accommodate fades that yield outages with probability 10^{-4}. Figure 14 shows the mean SNR required to achieve a certain CER with 99.99% reliability ($1-10^{-4}$ probability).

The single antenna SCM system requires approximately 21 dB larger mean SNR than the dual antenna OFDM system, at a CER of 10^{-4}. This is a very substantial reduction in the required mean SNR, and it translates into equally substantial improvements in two scenarios: a macrocell scenario, and a microcell scenario.

In the isolated macrocell scenario, we assume a path loss exponent of -4. Then the transmit power P_{tx} needed to deliver a SNR at the SU is given by

$$P_{tx} = SNR + 40 \log_{10}R + K$$

where K is a fixed constant. Let us consider a single antenna SCM system and a dual antenna VOFDM system with equal transmit powers. Let us adjust the cell radius of each

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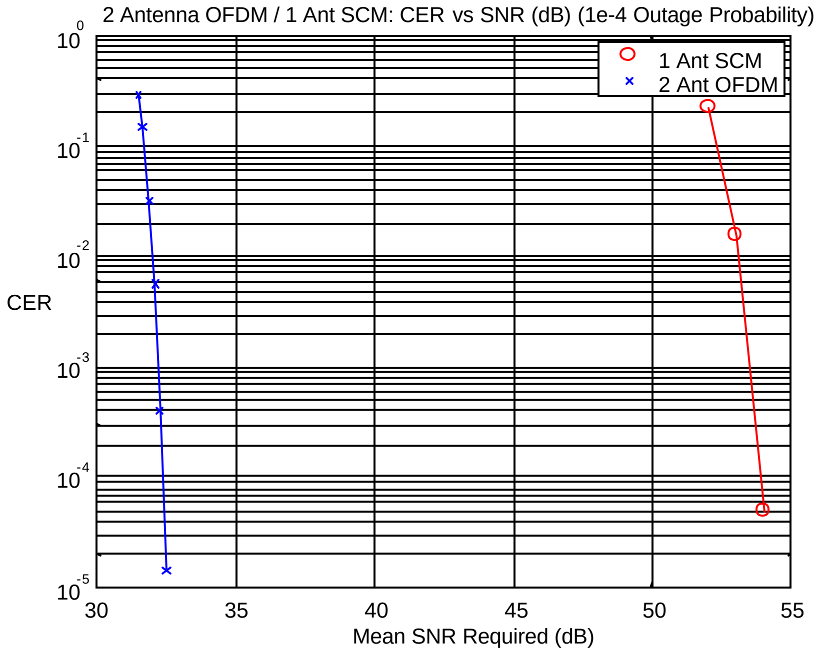

Figure 14: Performance of dual antenna VOFDM system compared to single antenna SCM system at 99.99% system availability.

system so that a SU at the cell edge receives the minimum mean SNR needed to achieve 10^{-4} CER and 10^{-4} outage probability. Then the cell radii are related by

$R_{ofdm} = 3.3 \times R_{scm}$

Hence, dual antenna diversity enables the cell radius to be more then tripled, and the cell coverage area to be increased by a factor of ten (all other factors being equal).

In the macrocell scenario, the range is limited by transmit power and receiver noise. By contrast, in the microcell scenario, the capacity is limited by the mean C/I. It is assumed that the statistics of observed C/I values are very similar to the statistics of the faded SNR. Hence the CER-SNR plot in Figure 14 may be applied to the microcell scenario in which the x-axis is replaced by C/I ratio. Hence Figure 14 shows that the OFDM and SCM systems have minimum required mean C/I ratios of 32.5 dB and 54 dB respectively.

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The capacity is determined by the frequency reuse plan. An M cell by N sector frequency plan has a spectral efficiency per area proportional to 1/(MN). However, the denser the plan (smaller MN), the lower the average C/I ratio the plan can deliver. Studies have shown that 3 cell by 3 sector system provides 32.5 dB of C/I for a 90% availability. Therefore, the dual antenna OFDM system considered in the example could support a 3 cell by 3 sector plan with 90% availability and outage probability of 99.99%.

By contrast, the single antenna SCM system requires 54 dB of C/I. This would correspond to a sparse plan with approximately 12-19 cells, at the same outage probability and availability. We feel a plan this sparse is not a good design. Our conclusion is that SCM cannot even produce a good design with the same reliability as the OFDM system.

However, if we are willing to accept a lower reliability in the SCM system, the minimum C/I required could be reduced. For example, an outage probability of 2.2e-3 corresponds to a SCM minimum C/I of 40 dB. With this lower C/I, a 7 cell by 6 sector plan becomes possible for SCM. This plan has lower spectral efficiency compared to the OFDM plan. The ratio of their spectral efficiencies is (7x6) / (3x3) = 4.67.

In summary, the dual antenna OFDM system is more than four times spectral efficient, and more than ten times reliable than the single antenna SCM system! The table below summarizes these two systems in the microcell scenario.

Modulation Type	Single Carrier	OFDM
Frequency Reuse Pattern	7 cell x 6 sector	3 cell x 3 sector
Relative Spectral Efficiency	1 Bits/Sec/Hz/Area	4.67 Bits/Sec/Hz/Area
Outage Probability	2e-3	1e-4

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7.5 Power Amplifier Back-Off

In terms of their input-output characteristics, transmitter power amplifiers are desired to be linear. For commercially available power amplifiers, the linearity is maintained for a large part of the input signal range. At large input values however, amplifier input-output characteristics are inevitably no longer linear. The output power where the deviation from linear reaches 1 dB is known as P1. The ratio of P1 to the average output power (or the difference in terms of dB power levels) is known as the power amplifier back-off. OFDM is known to be at a disadvantage as far as power amplifier back-off is concerned. This disadvantage was quantified experimentally by employing both OFDM and SCM. In this experiment, P1 = 48 dBm, and the maximum average output power is determined such that the out-of-band emission requirement of FCC is satisfied (for this case, it is the out-of-band noise floor due to nonlinearity that is important). The results are shown in the following table.

Power Output	Out-of-band specification		
(dBm)	60dBc	50dBc	40dBc
OFDM -16	35.0	37.7	39.9
QAM - 16	35.7	39.2	41.3
Difference	0.7	1.5	1.4
OFDM - 64	35.2	37.8	40.1
QAM - 64	35.9	39.2	41.1
Difference	0.7	1.4	1.0

Thus, the difference in power amplifier back-off between OFDM and SCM is of the order of 0.5-1.5 dB. Since VOFDM system provides an improvement in receiver sensitivity of many dBs, this difference in power amplifier back-off is rendered insignificant.

7.6 Phase Noise Requirement

OFDM systems require around 10 dB better phase noise than SCM systems for similar spectral efficiency. Although this difference may sound to be significant, the requirement can be satisfied at a small incremental cost, by means of better oscillators. These oscillators are available today without any new technology requirement. For example, the oscillators used in Direct Video Broadcast (DVB) systems are able to operate at 64QAM.

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7.7 Timing Offset

OFDM transmits data OFDM bursts, or effectively a larger “symbol” as compared to the individual symbols modulating each frequency component. Furthermore, the cyclic prefix provides redundant data around an OFDM burst. These factors make an OFDM system highly insensitive to timing offset. This feature of OFDM is widely documented (see, for example, [11, p. 78], [12, Ch. 5]).

7.8 Frequency Offset

OFDM systems have significant sensitivity to frequency offset. However, as in phase noise requirements, the techniques required are quite well established and can be implemented with little or no price impacts. There are various techniques published in the literature (see for example [12, Ch. 5]).

8 Summary and Conclusions

In this paper we provided a simulation- and experimentation-based comparison of Vector Orthogonal Frequency Division Multiplexing and Single Carrier Modulation systems for broadband wireless local loop applications. The results show that

- In the upstream direction where the operation is burst-mode, VOFDM is substantially superior to SCM. The CER performance of SCM, even with double-pass floating point precision RLS equalization, is unacceptable with a single antenna (for the same transmission overhead as a VOFDM system), and 3-9 dB worse than VOFDM with dual antennas.
- In the downstream direction where the operation is continuous demodulation, VOFDM provides dual antenna capability at a lower complexity. Low cost dual antenna SCM systems do not commercially exist today, and even if they were to be built, they would require significantly higher complexity. In the channel simulated (covering a large number of MMDS channels), SCM using LMS does not converge with a single antenna. It can work in a time-invariant channel with two antennas, but then, it does not work in a time varying channel with frequency 1 Hz. VOFDM performance does not deteriorate in this channel.

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- VOFDM has some limitations: power amplifier back-off and phase noise. Its power amplifier back-off requirements are about 0.5-1.5 dB lower than that of SCM. However, this difference is more than compensated for by means of better sensitivity receivers supplied in VOFDM. In terms of phase noise, the difference results in a small cost differential.

Overall, there is no doubt that VOFDM is superior to SCM for MMDS broadband wireless local loop applications. A given VOFDM MMDS broadband wireless local loop system will have a larger capacity than a comparable SCM one.

9 Acknowledgements

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