VOFDM Broadband Wireless Transmission and Its Advantages over Single Carrier Modulation

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***Abstract*- In this 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 it provides substantial performance improvements over SCM.**

I. 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.

OFDM is a method to solve the multipath problem. Although there are other techniques to solve this problem, 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. Unlike single carrier techniques, in OFDM, an equalizer is not used to equalize or invert the channel.

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.
6. At high sampling rates, computational complexity of OFDM is lower than space-time equalization techniques.

II. 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. 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.

III. PERFORMANCE COMPARISONS WITH SCM

A. VOFDM Exploitation of Multipath

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 fixed wireless 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 fixed wireless channels at 2.5 GHz band 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 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 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 1 and Figure 2 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. 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 low-cost SCM space-time equalizer products for fixed wireless 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 1 and Figure 2 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).

B. VOFDM and SCM in Continuous Carrier Demodulation

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 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.

16QAM results are shown in Figure 3 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 4. 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.

C. 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 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 5 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 5.

D. 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 6 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. For the macrocell scenario, dual antenna diversity enables the cell radius to be increased by a factor of 3.3; while for the microcell scenario, it can be calculated that while OFDM achieves 4.67 b/s/Hz/Area using a 3x3 frequency reuse pattern at an outage probability of 10^{-4}, SCM requires a 7x6 frequency reuse pattern to achieve 1 b/s/Hz/Area at an outage probability of $2x10^{-3}$ [11].

E. 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 (dBm)	Out-of-band specification		
	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.

F. 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.

VIII. 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 fixed wireless 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.
- 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.

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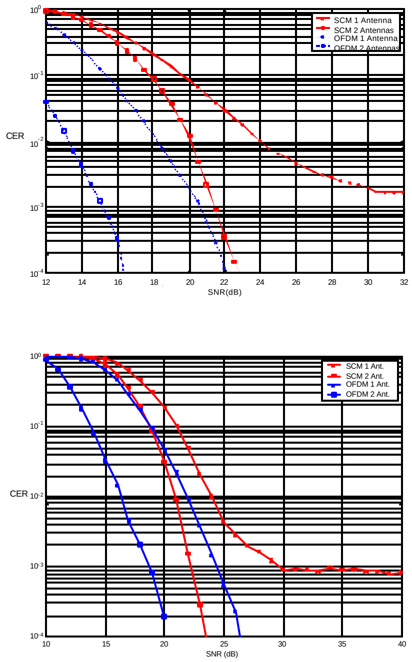

Figure 1: Upstream performance comparison of VOFDM and SCM using 16QAM. Upper figure: Channel 1,lower figure: Channel 2.

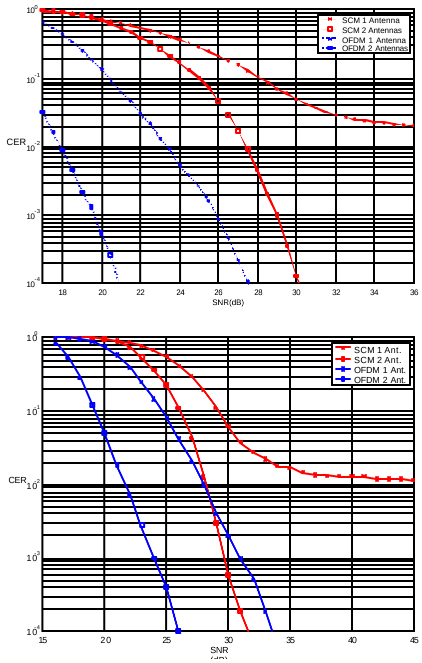

Figure 2: Upstream performance comparison of VOFDM and SCM using 64QAM. Upper figure: Channel 1, lower figure: Channel 2.

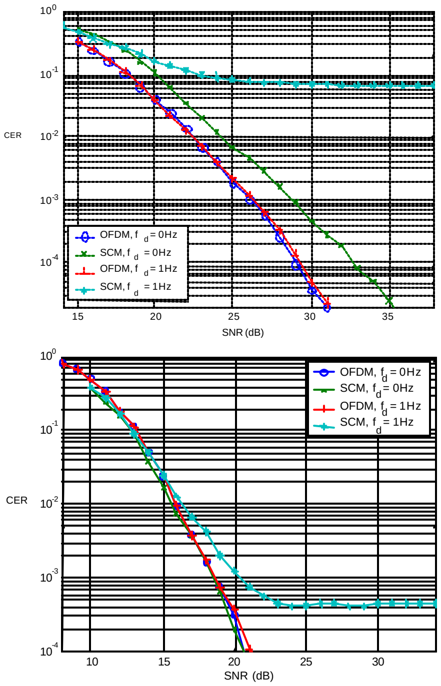

Figure 3: Downstream performance of VOFDM vs SCM with single and dual antennas on a time-varying channel using 16QAM. Upper figure: single antenna, lower figure: dual antenna.

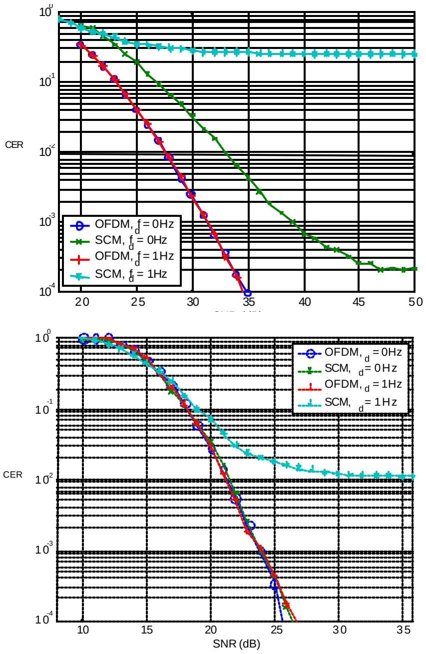

Figure 4: Downstream performance of VOFDM vs SCM with single and dual antennas on a time-varying channel using 64QAM. Upper figure: single antenna, lower figure: dual antenna.

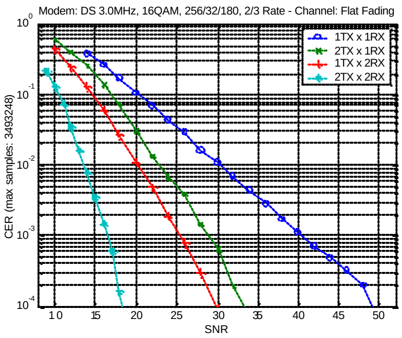

Figure 5: Simulation results for transmit diversity.

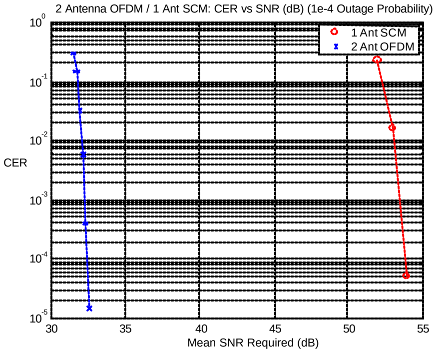

Figure 6: Performance of dual antenna VOFDM system.