A Multiple Sub-carrier Selection (MSCS) Diversity Architecture with Reduced Receiver Complexity for Wireless OFDM Applications

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***Abstract*—A simple multiple sub-carrier selection (MSCS) diversity combining receiver architecture for 802.11 OFDM wireless applications is proposed. This architecture can improve the system diversity performance with nearly the hardware simplicity of selection combining. A complex analog filter bank is inserted into antenna RF front end, which is also part of channel selection filter. By detecting the power level at each complex filter output, we can choose the optimum band from each antenna filter to maximize the receiver signal output. The added hardware complexity of the analog/RF receiver is minimal, and only a single A/D and DFT block are required.**

***Keywords*—OFDM, WLAN, receiver diversity, complexity, multiple sub-carrier, analog domain selection combining, smart antenna.**

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) has become popular for achieving a high data rate and combating multipath fading in wireless communications. Current standards for broadband wireless communications, such as IEEE 802.11a/g, ETSI-BRAN HIPERLAN/2 have adopted OFDM as the physical layer specification. OFDM divides the transmitting data stream into several parallel bit streams and modulating each of these data streams onto individual orthogonal sub-carriers. In other words, the entire frequency selective channel caused by the dispersive environment can be decomposed into multiple flat fading ones to effectively mitigate the effects of delay spread and inter-symbol interference (ISI).

To mitigate channel fading, multiple antennas in the receiver can be used to achieve spatial diversity. Multiple receiver antenna combining techniques can be split into two categories: frequency domain combining and time domain combining. Frequency domain combining can increase the performance of the OFDM system by combining signals based on the sub-carrier information after the DFT processor, whereas time domain combining does the same thing before the DFT processor, which relaxes the hardware complexity [1].

In terms of the bit error rate (BER) performance, the sub-carrier based combining technique is optimum. However as shown in Fig. 1, in order to retrieve sub-carrier information,

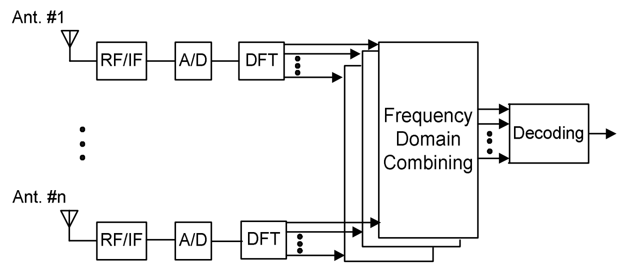

Figure 1. Block diagram of sub-carrier based combining receiver.

multiple A/D and DFT processors are required, one for each receive antenna. Therefore, frequency domain combining is also known as *post-DFT* combining [1]. Post-DFT combining can be difficult for mobile terminals (MT) due to the limitation of hardware complexity. There are three types of well known frequency domain combining techniques, selection diversity (SD), equal gain combining (EGC), and maximal ratio combining (MRC).

To reduce the hardware complexity of OFDM systems with multiple receive antennas, some time domain combining techniques have been proposed. In [1], the optimum diversity wideband weights have been derived by estimating the covariance matrix of the channel impulse response (CIR) for pre-DFT combining. The number of DFT processor can be reduced to one with some performance degradation. However the scheme still requires multiple A/Ds and is only applicable when the number of distinct paths in the channel is very limited [2]. In [3], the optimal sub-carriers can be selected based on the maximum absolute power in the time domain by transmitting repetitive OFDM symbols. Although the technique can have a minimal front-end hardware requirement and a single baseband demodulator, it does sacrifice the data transfer rate.

Hardware complexity can be dramatically reduced through simple antenna selection diversity as well. However for frequency selective channels, there always exists the possibility that some sub-carriers of an OFDM symbol demodulated from the selected antenna may have lower amplitude than the corresponding sub-carriers of the other receive antennas [3]. As a result, antenna selection diversity has less than optimum

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performance, with approximately 4~11dB SNR degradation compared to the case of optimum sub-carrier based Maximal Ratio Combining (MRC) for the case of two antennas [4]. Is there a technique whose performance can approach that of optimum sub-carrier combining but with the hardware simplicity of selection combining?

In this work, we propose a simple multiple sub-carrier selection diversity receiver architecture for WLAN OFDM systems with multiple antennas. With a small increase in analog complexity it is shown that a gain can be achieved by the proposed technique over selection diversity for WLAN OFDM systems. The technique requires only a single A/D and DFT, which eases the baseband hardware requirements significantly. For illustration purposes, we have selected the IEEE 802.11a PHY specification as the platform. However, readers with reasonable familiarity with the art should find the scheme generally applicable to other wireless OFDM standards.

II. SYSTEM DESCRIPTION

A block diagram of the proposed receiver architecture, with application to 802.11a OFDM in particular with multiple receive antennas is shown in Fig. 2. The signals from each receive antenna are downconverted to baseband, where they pass through an analog 2nd order complex filter bank with transfer functions given by (1) and plotted in Fig. 3.

$$T(s)=\frac{a_0\omega_0^{2}}{(s\pm j\omega_k)^2+(s\pm j\omega_k)\dfrac{\omega_0}{Q}+\omega_0^{2}} \tag{1}$$

where ω_0 is the pole frequency and ω_k is the frequency offset for the filter. In this case, three complex filters are chosen (low-pass, high-pass and band-pass) per receiver for minimum hardware complexity, as showed in Fig. 2. The output from the antenna with the highest RSSI is selected for each band, and the resulting signals are summed for an I/Q output to the A/D converter.

To meet the requirements of IEEE 802.11a for adjacent channel and non-adjacent channel rejection, a 5th order low-pass filter (LPF) is usually required for channel selection. For the proposed MSCS combining scheme, the complex filter bank can be part of the LPF, easing the requirements for the

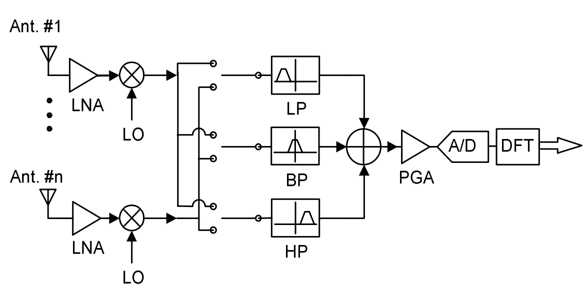

Figure 2. Block diagram of Multiple Sub-carrier Selection (MSCS) combining receiver architecture.

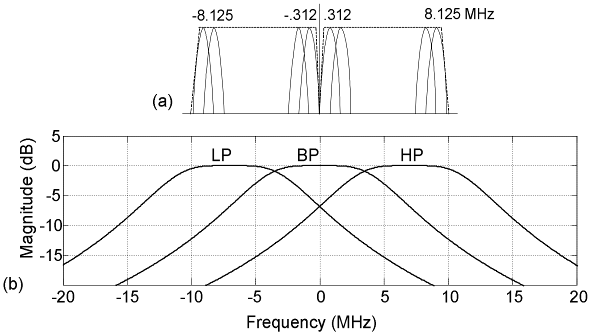

Figure 3. (a) Sub-carrier location of 802.11a. (b) Complex filter bank response.

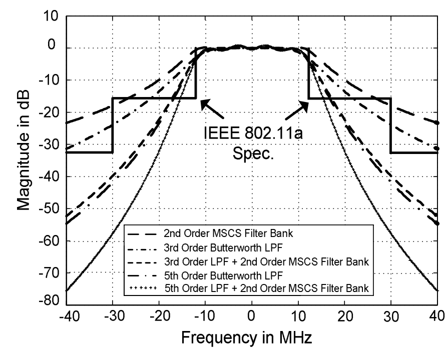

Figure 4. Filter Responses for Channel Selection.

channel selection filter. Fig. 4 shows that the combination of the 2nd order complex filter bank and a 3rd order real filter has nearly the same transfer function as a 5th order real filter.

In order minimize complexity, the analog complex filter bank is chosen to be 2nd order. This represents a compromise between complexity, settling time, and cancellation of signals from adjacent filter bands. A lower order filter may not be sharp enough for the rejection of the signal from adjacent filter bands and a new virtual "null" could be generated by the filter combining. This will be illustrated in Section IV.

III. ANALYSIS

With M antennas, each with an instantaneous $SNR=\gamma$, and n independent flat Rayleigh fading sub-bands, the general equation for the probability density function of the SNR for antenna selection diversity can be expressed as

$$p_{SD}(\gamma)=\frac{M\gamma^{n-1}}{n!\Gamma^{n}}e^{-\frac{\gamma}{\Gamma}}\left[(n-1)!\left(1-e^{-\frac{\gamma}{\Gamma}}\sum_{k=0}^{n-1}\left(\frac{\gamma}{\Gamma}\right)^{n-k-1}\frac{1}{(n-k-1)!}\right)\right]^{M-1} \tag{2}$$

where Γ is the mean SNR of each antenna (when no diversity is used). If we assume that the sub-bands covered by the complex filter bank all exhibit flat fading, then the performance of MSCS combining is equivalent to antenna selection with a single flat sub-band (n=1 in (2)) and is given by

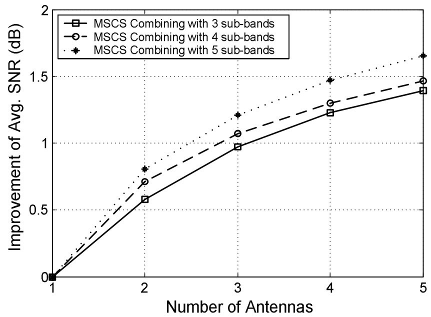

Figure 5. Improvement of average SNR for MSCS combining over Antenna Selection Diversity, from (4).

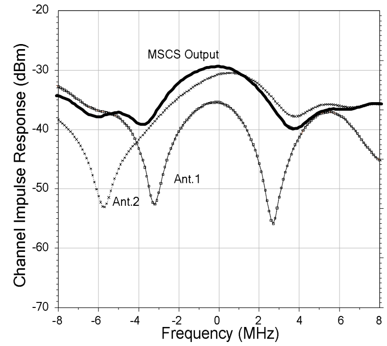

Figure 6. Simulated Channel Impulse Response: typical performance for MSCS combining with two antennas.

$$p_{MSCS}(\gamma) = \frac{M}{\Gamma} e^{-\frac{\gamma}{\Gamma}} \left(1 - e^{-\frac{\gamma}{\Gamma}}\right)^{M-1} \qquad (3)$$

The average SNR improvement of MSCS combining over antenna selection diversity can be evaluated in (4) and is plotted in Fig. 5.

$$\frac{\overline{\gamma_{MSCS}}}{\overline{\gamma_{SD}}} = \frac{\int_0^\infty \gamma p_{MSCS}(\gamma) d\gamma}{\int_0^\infty \gamma p_{SD}(\gamma) d\gamma} \qquad (4)$$

Fig. 5 shows that the performance improvement of MSCS combining over selection diversity (SD) increases with the number of antennas, and can be as high as 1.6 dB for five antennas. Meanwhile as the number of sub-bands n increases for a frequency selective channel, the performance of selection diversity (SD) will be degraded due to the increased possibility that some sub-carriers from the selected antenna may have lower amplitude than the corresponding sub-carriers of the other receive antennas. Therefore the improvement of MSCS combining over antenna selection becomes more significant, but more filters are also required.

IV. SIMULATION RESULTS

The system was simulated with the different data modes of IEEE 802.11a PHY layer [5]. In 802.11a, each channel is 20 MHz wide and includes 52 sub-carriers, each sub-carrier spacing is 312.5 KHz. One OFDM symbol duration is 4 μs, including a 0.8 μs guard interval and 3.2 μs effective IFFT/FFT period. The HIPERLAN/2 channel model "A" with 18 paths is used. This represents a "typical" office environment for non-line-of sight conditions and 50ns average rms delay spread [6].

Fig. 6 shows a typical channel impulse response simulation results. It clearly shows the benefits of MSCS combining. After MSCS combing, the deep nulls from two antenna inputs have been removed. Thus, MSCS combining will achieve better performance than simple antenna selection.

On rare occasions, the differing phase response in the analog filters create a new "virtual" channel null, as shown in Fig. 7. Obviously, when this happens the system performance

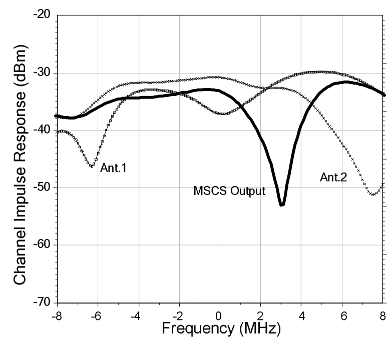

Figure 7. Simulated Channel Impulse Response: case with null generated by MSCS combining with two antennas.

maybe degraded, and antenna selection diversity provides the best performance.

For 54 Mb/s data rate mode of the IEEE 802.11a PHY layer with 64QAM modulation and ¾ coding rate [5], Fig. 8 shows the simulated average improvement of MSCS combining over Antenna Selection is about 1dB for both favorable and non-favorable cases, in good agreement with (4).

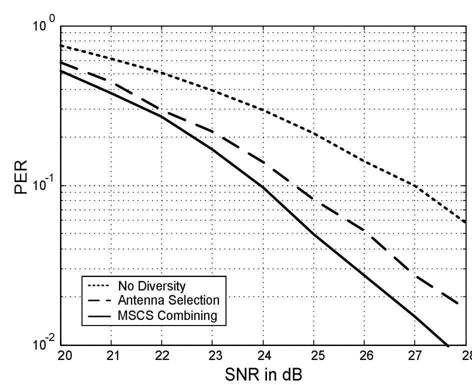

Figure 8. PER performance of IEEE 802.11a 54Mb/s mode with dual antennas and different combining schemes.

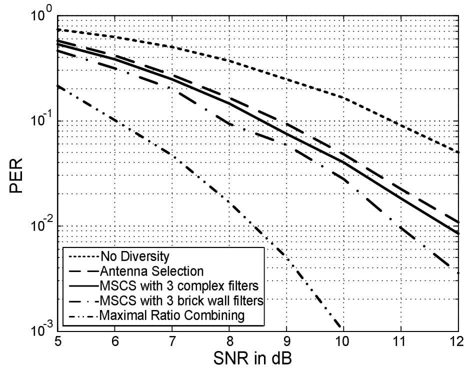

Figure 9. PER performance of IEEE 802.11a 12Mb/s mode with dual antennas and different combining schemes.

For 12 Mb/s data rate mode with QPSK modulation and ½ coding rate, the improvement of MSCS combining over Antenna Selection is very limited as shown in Fig. 9. Notice that even with 3 ideal filters, the improvement is still only about 1dB. As expected, maximal ratio combining has the best performance.

V. CONCLUSIONS

The proposed multiple sub-carrier selection (MSCS) combining receiver is capable of achieving diversity gains with only a small increase in receiver complexity. This simple analog technique is also anticipated to be a good candidate for OFDM systems using a more complex frequency domain combining. For example, in a system with four receive antennas, MSCS combining can be employed to yield two outputs with an optimized SNR for subsequent MRC thereby requiring only two complex A/Ds and DFTs.

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