Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**Space-frequency bit-interleaved coded modulation for MIMO-OFDM/OFDMA systems**
Date Submitted	**2004-11-04**
Source(s)	Sumeet Sandhu, Nageen Himayat, Shilpa Talwar, David Cheung, Qinghua Li **Intel Corporation** sumeet.sandhu@intel.com Voice: +1-408-765-8558
Re:	
Abstract	One of the smart antenna options in the 802.16e and 802.16d standards is multiple-input, multiple-output (MIMO) systems. MIMO requires multiple antennas at both the base station (BS) and subscriber station (SS). With M antennas at the BS and SS, the point-to-point throughput can be multiplied by M times. The high throughput MIMO mode consists of simple spatial multiplexing on upto 4 transmit antennas, with no coding across antennas. An independent spatial stream with frequency-only bit-interleaved coded modulation (F-BICM) is transmitted on each antenna. That is, the convolutionally coded input bits are interleaved across frequency tones but not across antennas. Here we propose space-frequency bit-interleaved coded modulation (SF-BICM) which provides both frequency diversity and spatial diversity by interleaving coded bits across transmit antennas and frequency tones. Performance of the proposed SF-BICM is compared to spatial multiplexing (F-BICM) using 802.16e-like coding and modulation over ITU channel models. Performance is demonstrated with minimum mean squared error (MMSE) spatial receivers per tone. The proposed SF-BICM outperforms F-BICM by 2-10 dB for 1000 byte packets.
Purpose	Adoption of proposed changes into P802.16e ~~Crossed-out indicates deleted text,~~ underlined blue indicates new text change to the Standard
Notice	
Release	
Patent Policy and Procedures	

Space-frequency bit-interleaved coded modulation for MIMO

Sumeet Sandhu, Nageen Himayat, Shilpa Talwar, David Cheung, Qinghua Li
Intel Corporation

Abstract

Section 8.4.8 in 802.16e draft standard [1] provides several transmit diversity options for MIMO, including spatial multiplexing. This paper presents the design of a novel space-frequency bit-interleaver for MIMO-OFDM systems. The proposed space-frequency interleaver (SFI) interleaves coded bits across both transmit antennas and frequency tones based on space-frequency diversity principles. Performance is demonstrated for an IEEE 802.16e-like OFDM PHY layer using ITU channel models. The proposed space-frequency interleaver outperforms a frequency-only interleaver by 2-10 dB for 1000 byte packets.

1 Introduction

A number of modern wireless communication standards are based on the orthogonal frequency-division modulation (OFDM) physical layer (PHY). Key examples are the IEEE 802.11a [1] and IEEE 802.11g standards for wireless local area networks (WLAN), and IEEE 802.16d and IEEE 802.16e standards for wide area cellular networks (WAN). OFDM has several advantages over other common PHY layers such as single carrier and spread spectrum, one of which is low implementation complexity. More importantly, OFDM provides a high degree of frequency diversity even with simple coding schemes such as convolutional coding followed by bit-interleaved coded modulation (BICM) across frequency tones [4].

In order to increase range and link throughput, multiple antenna options have been proposed in the next generation enhancements to 802.11a/g and 802.16d/e. In particular, multiple-input, multiple-output systems (MIMO) are an integral part of high throughput proposals submitted to Task Group 802.11n. MIMO has already been approved as one of the smart antenna options in the 802.16d standard [2], and has also been proposed to Task Group 802.16e[3]. The high throughput MIMO code proposed to TG 802.16e consists of simple spatial multiplexing with no coding across antennas.

Just as it is possible to extract almost full frequency diversity over single antenna OFDM with well-designed BICM, additional spatial diversity offered by MIMO systems can also be extracted by careful design of space-frequency BICM. In this paper we propose a novel space-frequency interleaver (SFI) that provides both frequency diversity and spatial diversity by interleaving convolutionally coded bits across transmit antennas and frequency tones [6]. The interleaver design is inspired by space-frequency block codes (SFBC) previously presented in [5]. Performance of the proposed interleaver is compared to spatial multiplexing (frequency-only interleaver) using 802.16e-like coding and modulation over ITU channel models [7]. Performance is demonstrated with minimum mean squared error (MMSE) spatial receivers per tone.

Previous work on BICM for MIMO-OFDM including [8],[9] and [10] was primarily focused on maximum a posteriori and iterative spatial receivers rather than the MMSE spatial receiver. The pairwise error probability analysis in [8] established coding gain as a more important design metric than diversity gain for channels with high frequency diversity. Here we demonstrate the importance of designing for diversity gain with MMSE spatial receivers. The paper is organized as follows. Section 2 provides an overall system description in terms of 802.16e and the input-output equation. Section 3 describes the interleaver design in detail. Section 4 shows simulation results, and Section 5 provides key conclusions.

2 Bit mapping in 802.16e SISO OFDMA PHY

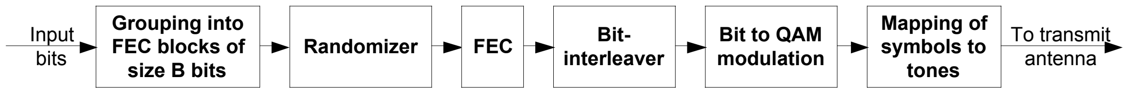

Figure 1: IEEE 802.16e mapping of uncoded bits to OFDM tones on a single antenna

The mapping of uncoded bits to OFDM tones on a single antenna is shown in Figure 1. The input is uncoded bits and the output is QAM symbols mapped to tones in the assigned subchannels. After all tones in the FFT block have been filled up with symbols, the frequency domain signal is converted to the time domain via the inverse Fast Fourier Transform (I-FFT), prefixed with the cyclic prefix, upconverted to the carrier frequency and launched over the transmit antenna. The bit to tone mapping consists of the following steps

1) Grouping of bits into blocks of size B, where B = 6, 12, 24, …, 48 bytes depending on the QAM size.
2) Scrambling of bits in one block
3) FEC coding of bits in one block (convolutional coding followed by puncturing)
4) Bit interleaving of bits in one block
5) Mapping of interleaved bits to QAM symbols
6) Mapping of QAM symbols to tones in the assigned subchannel

Here *step 4* distributes the adjacent coded bits across tones so as to provide frequency diversity. In general, adjacent bits in a convolutionally coded sequence must be placed on tones separated by at least one coherence bandwidth in order to extract full frequency diversity in a frequency selective channel. A regular spacing of adjacent bits across tones is sufficient. For example, 48 coded inputs bits indexed as 1, 2, 3, …, 48 are mapped to 48 tones for BPSK modulation in 802.11a as shown below.

Example A: 802.11a OFDM PHY : data tones=48, interleaving depth=3, BPSK modulation

```
1 BITS per BPSK symbol, mapped to tones 1:48
  1     17     33      2     18     34      3     19     35      4     20     36      5     21     37      6     22     38      7
 23     39      8     24     40      9     25     41     10     26     42     11     27     43     12     28     44     13     29
 45     14     30     46     15     31     47     16     32     48
```

Here adjacent bits *i* and *j* are separated by at least 3 tones for all *i*. This regular spacing extracts most of the maximum possible frequency diversity corresponding to delay spreads equal to the cyclic prefix (equal to 16 time samples, for a 64-point FFT, sample time = 50 ns).

Although regular spacing of bits maximizes the performance of a point-to-point OFDM link, it may not be robust in the presence of co-channel interference in a multi-cellular OFDMA system like 802.16e. If one of the OFDMA users is assigned a regularly spaced subset of tones, it may suffer high interference from an extra-cellular user assigned the same set of tones. In order to provide robustness against interference, *step 6* assigns adjacent bits to irregularly spaced tones spread throughout the spectrum. An example is shown below for 1 FEC block of 96 bits which is mapped to rate _ QPSK symbols on 1 FUSC sub-channel consisting of 48 tones in an FFT size of 512 tones.

Example B: 802.16e FUSC DL: 1 sub-channel, 1 FEC block, 48 data tones, rate _ QPSK

```
2 BITS per QPSK symbol
     1     33     65      2     34     66      3     35     67      4     36     68      5     37
    17     49     81     18     50     82     19     51     83     20     52     84     21     53
  Columns 15 through 28
    69      6     38     70      7     39     71      8     40     72      9     41     73     10
    85     22     54     86     23     55     87     24     56     88     25     57     89     26
  Columns 29 through 42
    42     74     11     43     75     12     44     76     13     45     77     14     46     78
    58     90     27     59     91     28     60     92     29     61     93     30     62     94
  Columns 43 through 48
    15     47     79     16     48     80
    31     63     95     32     64     96
```

```
Columns of BITS above are mapped to the following TONES
  Columns 1 through 14
    46    60    64    75    84    97   103   107   117   131   135   146   154   167
  Columns 15 through 28
   173   177   186   201   205   216   223   237   243   246   256   271   276   287
  Columns 29 through 42
   294   309   315   318   328   342   347   358   365   379   387   390   401   415
  Columns 43 through 48
   420   431   438   451   458   461
```

The separation between adjacent tones above is irregular, but is equal to 9 on average, which is what the separation would have been between regularly spaced tones as shown below (ignoring pilot locations, which can be adjusted for).

```
Potential mapping to regularly spaced TONES
  Columns 1 through 14
    46    55    64    73    82    91   100   109   118   127   136   145   154   163
  Columns 15 through 28
   172   181   190   199   208   217   226   235   244   253   262   271   280   289
  Columns 29 through 42
   298   307   316   325   334   343   352   361   370   379   388   397   406   415
  Columns 43 through 48
   424   433   442   451   460   469
```

3 Proposed bit mapping for 802.16e MIMO-OFDMA

Our space-frequency interleaver design is motivated by the space-frequency code design in [5], where it was suggested that linearly coded QAM symbols should be placed in diagonals along the space-frequency codeword in order to extract full diversity at full rate. What we propose is as follows: treat the adjacent coded bits as coded symbols, and interleave them according to the optimal diversity pattern suggested by SFBC design. An interleaver along these lines was proposed in [6] for 802.11a systems.

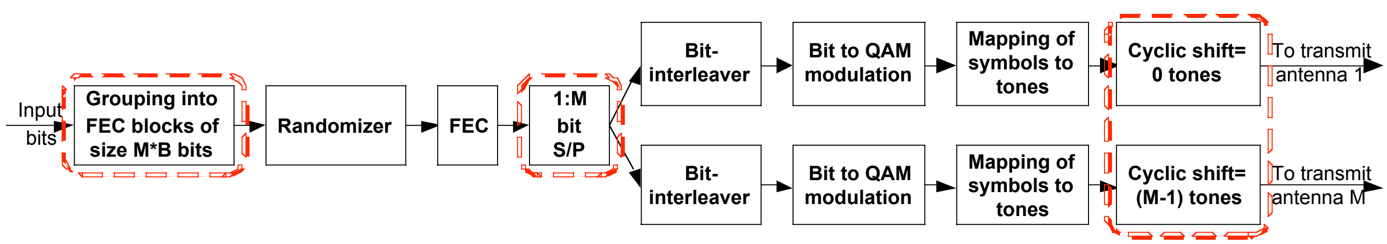

Figure 2: Proposed SF-BICM mapping of bits to multiple antennas

Here we propose a similar space-frequency interleaver for 802.16e MIMO-OFDMA, consisting of the following 4 steps illustrated in Figure 2 above. The proposed modifications to the existing 802.16e bit-to-tone mapping are steps 1, 2 and 4 as circled in red above.

1) **FEC blocks:** Group the incoming uncoded bits into blocks of size M*B, where M is the number of transmit antennas. It is important to create larger FEC blocks to preserve frequency diversity going from SISO to MIMO systems. If the FEC block size is held constant and B bits are mapped to 1/M of the SISO tones on M antennas, spreading across fewer tones on each antenna will not provide full frequency diversity.
2) **Antenna multiplexing:** Coded bits are serial to parallel converted and multiplexed to different antennas. Let the total number of bits = $M*N_{CBPS}$, where M is the number of transmit antennas and N_{CBPS} is the number of coded bits per OFDM symbol. The bits indexed by $m{:}M{:}M*N_{CBPS}$ are mapped to the m^{th} antenna.
3) **802.16e interleaving, modulation and tone mapping:** The resulting groups of N_{CBPS} bits on each antenna are interleaved according to the 802.16e interleaver and Gray mapped to QAM symbols. The resulting QAM symbols are mapped to tones in the assigned 802.16e sub-channels.
4) **Cyclic tone shift:** The final step consists of introducing a cyclic shift of $m-1$ tones to the symbol sequence mapped to the m^{th} antenna. This ensures that adjacent coded bits aren't mapped to the same

tone on different antennas. If adjacent coded bits get mapped to the same tone on different antennas, an MMSE receiver results in correlated noise on all these bits thus degrading performance. Placing adjacent coded bits on different tones on different antennas de-correlates noise on adjacent bits, thus improving performance and providing greater spatial diversity.

Note that the amount of cyclic shift may be greater than 1 tone from antenna to antenna. In general, the optimum cyclic shift must be determined by simulation for different rates and MIMO configurations. The maximum cyclic shift is equal to N_{DS}/M, where N_{DS} = number of data tones that 1 FEC block is mapped to. *Note that step 2 in the interleaver design provides spatial diversity with ML/MAP receivers, steps 1 and 3 provide frequency diversity, and step 4 provides spatial diversity with linear receivers that induce correlation among tones and antennas (e.g. MMSE).*

4 Simulation Results

This section demonstrates performance of the proposed SF-BICM over 1x1 and 4x4 MIMO systems with 512-point FFT (384 data tones). The 4x4 MIMO architecture transmits 4 times the data rate of the 1x1 SISO, and uses an MMSE receiver to recover 4 bit streams. Two ITU channel models are used to generate iid frequency selective channels between each transmit-receive antenna pair: the Pedestrian model A with a low rms delay spread of 45 ns, and the Vehicular model B with a high rms delay spread of 4000 ns. No spatial correlation is induced between transmit or receive antennas. Packet error rate is computed for 1000 byte packets. The entire packet is encoded as a single FEC block that is mapped to multiple tones and OFDM symbols in a simple fashion similar to 802.11a (the 802.16e mapping of QAM symbols to sub-channel tones is ignored here). Two extreme rates are considered: rate _ QPSK and rate _ 64-QAM. We assume perfect channel estimation, phase and carrier tracking and symbol synchronization, and floating point precision. In addition to SISO and proposed SF-BICM (labeled CTS96 in Figure 4), we also simulate a simpler spatial multiplexing system (labeled SM in Figure 4) which is shown in Figure 3.

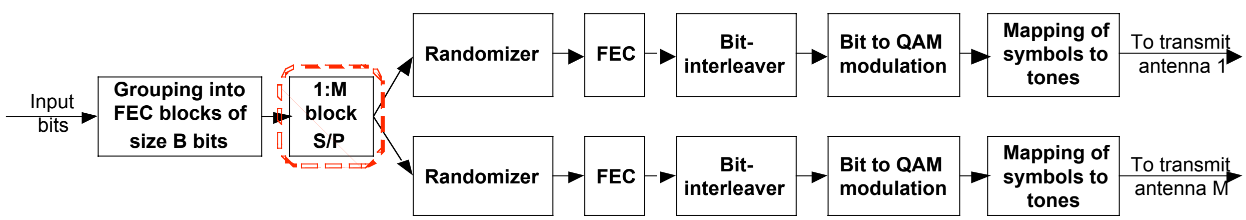

Figure 3: Simple spatially multiplexed mapping of bits to multiple antennas

The SM interleaver takes consecutive blocks of B bits and multiplexes them to different antennas. Therefore bits on different transmit antennas are independent. This method is expected to provide some frequency diversity but no spatial diversity.

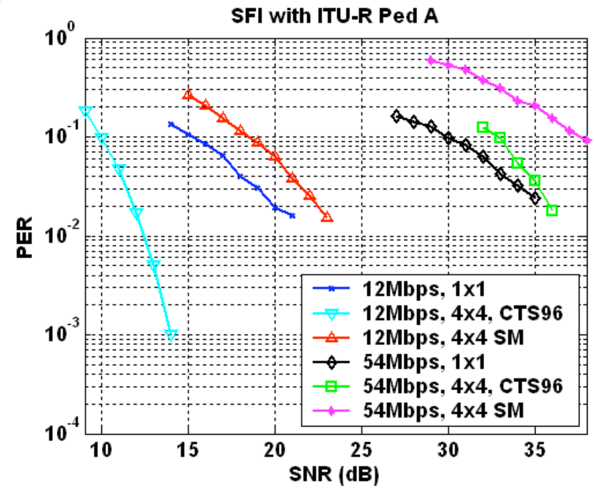

Figure 4(a): PER for 45 ns rms delay spread channels

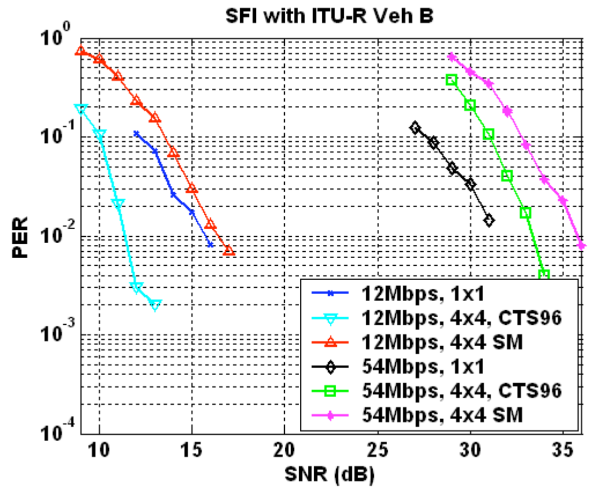

Figure 4(b): PER for 4000 ns rms delay spread channels

Consider Figure 4(a). At the high rate, 4x4 MIMO loses range at 4 times the throughput of 1x1. At the low rate, however, 4x4 MIMO with the proposed SFI (CTS96) actually gains range (8+ dB at PER 1%). Spatial multiplexing which only interleaves across frequency and not across antennas is 10+ dB worse than SFI at 1 % PER. Note that the slopes of MIMO+SFI are sharper than those of MIMO+SM, suggesting better diversity. Figure 4(b) follows the same trends as Figure 4(a). The key difference is that ITU VehB provides much more frequency diversity than ITU PedA. As a result, the advantages of SFI are not as sharp as in Figure 4(a). For example, the gain of SFI over SM is only 2 dB at the high rate at 10% PER. The MMSE receiver induces correlation across antennas because of cross-talk, and the channel induces correlation across tones because of limited delay spread. This combination ends up correlating adjacent tones on all antennas. Our proposed interleaver places bits on uncorrelated tones and antennas, thereby improving performance with the MMSE receiver.

5 CONCLUSIONS

It is important to design BICM for MIMO-OFDM systems to exploit full spatial and frequency diversity. A good space-frequency interleaver design was proposed in this paper. It provides gains of 2-10 dB at packet error rates of 1-10% and modulations of rate _ QPSK to rate _ 64-QAM. Interleaver complexity is negligible compared to the overall modem, therefore this is a significant and easily achieved gain in performance over simple spatial multiplexing.

Acknowledgments

The authors would like to thank Wendy Wong of Intel Corporation for help with interpretation of the IEEE 802.16e specification.

References

[1] *High-speed Physical Layer in the 5 GHz Band*, IEEE Std 802.11a-1999.
[2] *Air Interface for Fixed Broadband Wireless Access Systems*, IEEE P802.16-REVd/D5, May 2004.
[3] *Air Interface for Fixed and Mobile Broadband Wireless Access Systems*, IEEE P802.16e/D4, August 2004.
[4] H. Heiskala and J. Terry, OFDM Wireless LANs: A Theoretical and Practical Guide, SAMS, 2002.
[5] L. Shao, S. Sandhu, S. Roy, M. Ho, "High rate space frequency block codes for next generation 802.11 WLANs", *Proceedings of International Conference on Communications,* Vol 5, pp. 2995-2999, June 2004.
[6] S. Sandhu, "Space-frequency interleaving for MIMO-OFDM," *Intel report*, December 2003.
[7] ITU channel models reference
[8] I. Lee, A.M. Chan, C.-E.W. Sundberg, "Space-time bit-interleaved coded modulation for OFDM systems," *IEEE Transactions on Signal Processing,* Vol 52, number 3, pp. 820-825, March 2004.
[9] K.-B. Song, C.-S. Hwang and J.M. Cioffi, "Rate-compatible punctured convolutionally (RCPC) space-frequency bit-interleaved coded modulation (SF-BICM)," *Proceedings of International Conference on Communications,* Vol 6, pp. 3284-3288, June 2004.
[10] D. Rende and T.F Wong, "Bit interleaved space-frequency coded modulation for OFDM systems" *Proceedings of International Conference on Communications,* Vol 4, pp. 2827-2831, May 2003.