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| 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 | **2005-01-26** | |
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| Re: | | |
| Abstract | Draft 802.16e/D5a contains references ~~references~~ to horizontal and vertical encoding architectures as means to map spatially multiplexed schemes to multiple antennas. However, the exact details of the mapping are not specified. Interleaving of spatial streams across antennas is important to achieve spatial diversity for MIMO systems. ~~for MIMO.~~ Starting on page 362, the vertical encoder proposed for spatially-multiplexed MIMO systems does not specify details of the blocks shown in Figure 251c, i.e. the Encoder, Modulation, Demux and Sub-carrier mapping/PRBS blocks. It is important to design these blocks carefully to fully exploit spatial and frequency diversity with all types of receivers.<br>In this contribution we propose space-frequency bit-interleaved coded modulation (SF-BICM) “vertical-encoded” architecture which interleaves FEC blocks across both spatial streams and frequency tones. Spatial streams are multiple data streams transmitted over multiple antennas, both in open-loop and closed-loop modes. Space-frequency interleaving provides spatial diversity in addition to frequency diversity, especially with minimum mean squared error (MMSE) spatial filters per tone. Performance of the proposed SF-BICM is compared to simple spatial multiplexing (F-BICM) over 2x2 spatially i.i.d ITU channels. The proposed SF-BICM outperforms F-BICM by 1-3 dB for 200 byte packets. Additional advantages of the proposed SF-BICM scheme is that it does not involve any redesign of existing SISO blocks as well as the SF-BICM architecture works well with adaptive bit loading MIMO algorithms. | |
| Purpose | Adoption of proposed changes into P802.16e.<br>~~Crossed-out indicates deleted text,~~ underlined blue indicates new text change to the Standard | |
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# Space-frequency bit-interleaved coded modulation for MIMO

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## 1 Background

The spatial multiplexing MIMO modes in sections 8.4.8.3.3, 8.4.8.3.4, 8.4.8.3.5, 8.4.8.4.3, and 8.4.8.9 consist of simple spatial multiplexing on 1-4 transmit antennas, with no coding across transmit antennas. The standard does not specify how the spatial streams are mapped to several antennas. Example embodiments are illustrated in figures 251c/d in 802.16D5a, where two modes related to “horizontal” and “vertical” encoding are illustrated. In horizontal encoding, on each antenna, independent spatial streams with frequency-only bit-interleaved coded modulation (F-BICM) are transmitted. That is, FEC blocks of convolutionally-coded input bits are interleaved across frequency tones but not across transmit antennas. In vertical encoding each FEC encoded block is interleaved and mapped to QAM symbols, before the symbols are split across multiple streams
~~On each antenna, independent spatial streams with frequency-only bit-interleaved coded modulation (F-BICM) are transmitted. That is, FEC blocks of convolutionally-coded input bits are interleaved across frequency tones but not across transmit antennas.~~

In this contribution we propose space-frequency bit-interleaved coded modulation (SF-BICM) which interleaves FEC blocks across both transmit antennas (or spatial streams) and frequency tones. Space-frequency interleaving provides spatial diversity in addition to frequency diversity, especially with minimum mean squared error (MMSE) spatial filters per tone. Additional, advantages of our proposed SF-BICM scheme is that it does not involve any redesign of existing SISO blocks and is also a suitable architecture for adaptive bit loading algorithms (ABL), which are further covered in [6]. SF-BICM is “vertically encoded” structure architecture which is well-suited for spatial interleaving of convolutional codes.

## 2 Proposed text change

*[Add the following text as section 8.4.8.3.1 and renumber sections 8.4.8.3.1-6 as 8.4.8.3.2-7]*
~~***[Add a new section 8.4.8.10 as follows]***~~

### 8.4.8.3.1~~10~~ ~~Space-frequency bit-interleaved coded modulation (SF-BICM)~~Vertical encoding architecture for Convolutional Encoded MIMO

This section describes 4 steps for mapping bits to multiple spatial streams and tones for convolutionally encoded MIMO. The key changes are steps 1, 2 and 4, and are circled in red in the figure below.

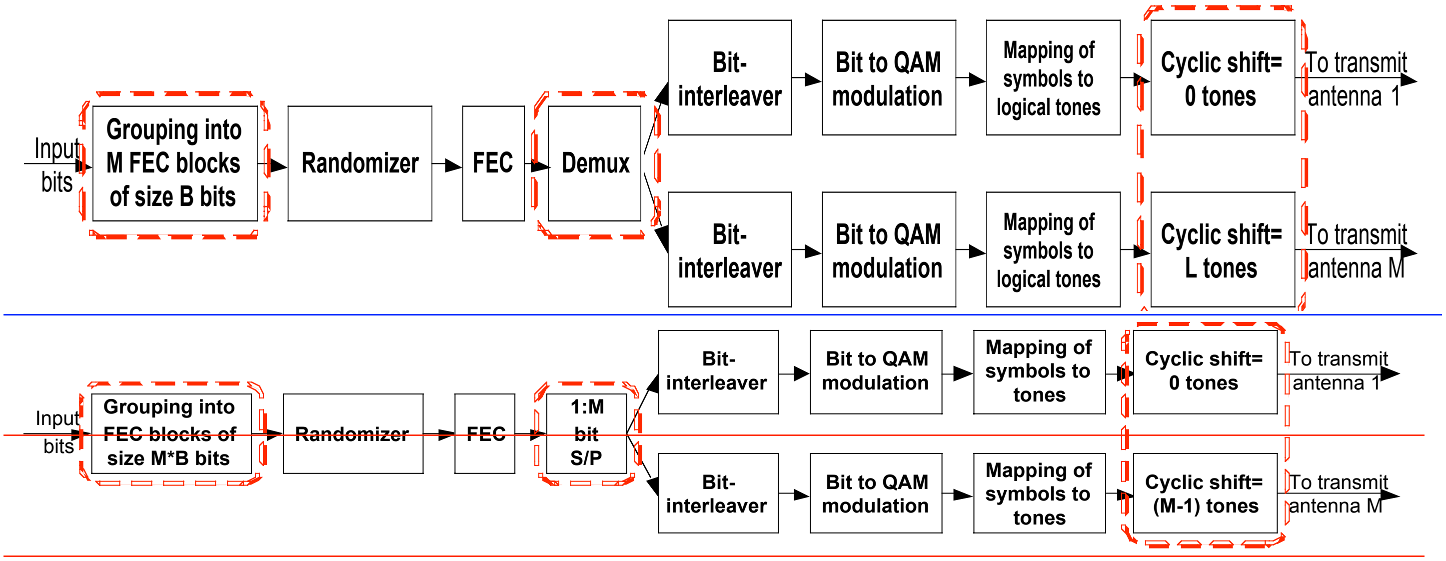


**Figure ~~1~~xxx: Space-frequency bit-interleaved coded modulation (SF-BICM)**

Let $M$ be the number of spatial streams (where $M$ is less than or equal to the number of transmit antennas), $B$ the number of uncoded bits in 1 SISO FEC block, $N_{CBPS}$ the number of coded bits per convolutionally-coded FEC block (as in Section 8.4.9), $N$ the FFT size, $N_{DS}$ the number of tones occupied by $N_{CBPS}$ bits, ~~and~~ $q$ the number of bits per QAM symbol and $N_U$ is the number of tones assigned to a user.~~.~~

## ~~SF-BICM TRANSMITTER~~VERTICAL ENCODING TRANSMITTER FOR CONVOLUTIONAL CODES

1) **FEC encoding:** The incoming uncoded bits are grouped into $M$ blocks of size ~~$M$~~$B$ and encoded with the usual convolutional code and punctured. The coded output blocks are of size ~~$M$~~$N_{CBPS}$.

~~1)~~

The following steps apply to each FEC block.

2) **Serial to parallel multiplexing (Demux):** The demultiplexer extracts bits for the chains one by one from its input bit sequence. The bits to the chain with higher modulation order are extracted before those with lower modulation order. Denote the number of bits per subcarrier on the $m$-th chain as $L_m$, where $L_1 \geq \cdots \geq L_M$. The demultiplexer first extracts the bits for the chain with the greatest modulation order as follows. The $i$-th extracted bit is the $k$-th bit in the original input bit sequence, where $k = \text{round}\left(\frac{i}{L_1}\sum_{m=1}^{M} L_m\right)$. For the $p$-th chain, the $i$-th extracted bit is the $k$-th bit in the remaining bits after the extractions for the previous $p-1$ chains, where $k = \text{round}\left(\frac{i}{L_p}\sum_{m=p}^{M} L_m\right)$. For uniform loading on each spatial streams, the Demux operation reduces to a serial to parallel conversion. ~~The FEC block is multiplexed to different spatial streams. The bits indexed by $m{:}M{:}MN_{CBPS}$ are mapped to the $m^{th}$ spatial stream for $m=1,\ldots,M$.~~

3) **802.16e interleaving and tone mapping:** The resulting groups of $N_{CBPS}$ bits on each spatial stream are interleaved according to the 802.16e interleaver and Gray mapped to QAM symbols. The resulting QAM symbols are mapped to $N_{DS}$ logical tones according to 802.16e sub-channelization and tone-mapping. The same set of tones is occupied on each spatial stream.

4) **Cyclic tone shift:** The final step consists of cyclically shifting the symbol sequence mapped to the $m^{th}$ spatial stream by $L = (m-1)\ .\ (N_U/M)$ tones to the right.

### ~~SF-BICM RECEIVER~~VERTICAL ENCODING RECEIVER FOR CONVOLUTIONAL CODES

In order to map received symbols to bit estimates, the receiver performs steps 1-4 in the reverse order. The output of the per-tone spatial demapper such as MMSE or ML is soft bits.

1) **Reverse cyclic tone shift:** The soft bits on the $m^{th}$ spatial stream are shifted to the left by $L = (m-1) . (N_U/M)$ ~~$m-1$~~ tones.
2) **802.16e tone demapping and de-interleaving:** The bits on each spatial stream are demapped and de-interleaved to 802.16e tone-demapping and deinterleaving.
3) **Parallel to serial de-multiplexing:** Bits on different spatial streams are de-multiplexed into a single stream of ~~$M$~~$N_{CBPS}$ bits. The inverse of the Demux operation is used.
4) **FEC decoding:** The soft coded bits are decoded with the 802.16e depuncturer and convolutional decoder.

# 3 Sample outputs of SISO and MIMO interleavers

## 3.1 SISO interleaver

The mapping of uncoded bits to OFDM tones on a single antenna is shown in Figure 2. The input is uncoded bits and the output is QAM symbols mapped to tones in the assigned sub-channels. 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.

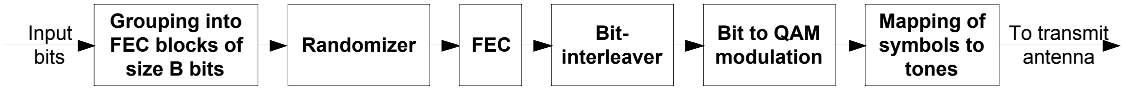


**Figure 2: IEEE 802.16e mapping of uncoded bits to OFDM tones on a single antenna**

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.

## 3.2 Proposed MIMO interleaver

The proposed modifications to the existing 802.16e bit-to-tone mapping are steps 1, 2 and 4 as circled in red below.

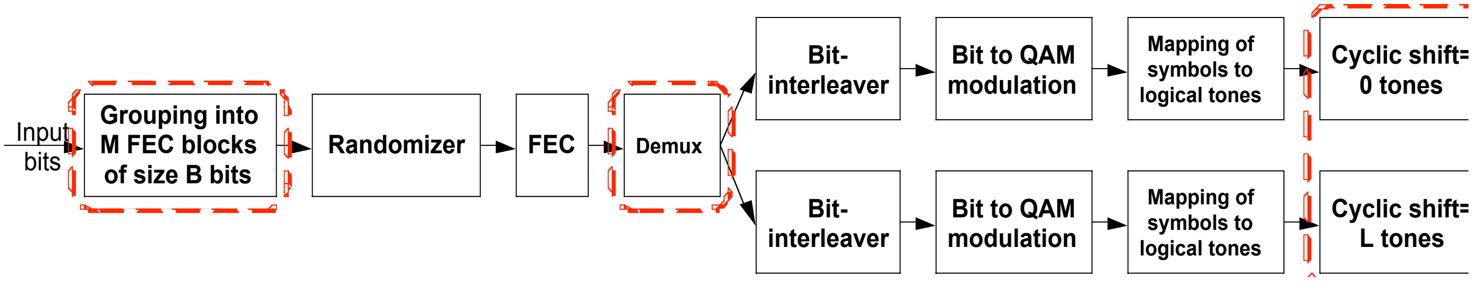


**Figure 3: Proposed SF-BICM mapping of bits to multiple antennas (or spatial streams)**

1) **FEC encoding:** Group the incoming uncoded bits into *M* blocks of size ~~*M*~~*B*, such that the coded output blocks are of size ~~*M*~~$N_{CBPS}$. It is important to create larger FEC blocks to preserve frequency diversity going from SISO to MIMO systems. If the FEC block size were held constant and $N_{CBPS}$ bits were mapped to *1/M* of the SISO tones on *M* antennas, spreading across fewer tones on each antenna will not

provide full frequency diversity. However, we choose to restrict our block sizes to *B* bits in order to maintain compatibility with the existing standard.

2) **Serial to parallel antenna multiplexing (Demux):** The demultiplexer extracts bits for the chains one by one from its input bit sequence. The bits to the chain with higher modulation order are extracted before those with lower modulation order. Denote the number of bits per subcarrier on the $m$-th chain as $L_m$, where $L_1 \geq \text{L} \geq L_M$. The demultiplexer first extracts the bits for the chain with the greatest modulation order as follows. The $i$-th extracted bit is the $k$-th bit in the original input bit sequence, where $k = \text{round}\left(\frac{i}{L_1}\sum_{m=1}^{M} L_m\right)$. For the $p$-th chain, the $i$-th extracted bit is the $k$-th bit in the remaining bits after the extractions for the previous $p-1$ chains, where $k = \text{round}\left(\frac{i}{L_p}\sum_{m=p}^{M} L_m\right)$. For uniform loading on each spatial streams, the Demux operation reduces to a serial to parallel conversion.

~~2)~~3) ~~Coded bits are serial to parallel multiplexed to different antennas. The bits indexed by~~ ~~$m{:}M{:}MN_{CBPS}$~~ ~~are mapped to the~~ ~~$m^{th}$~~ ~~antenna.~~

~~3)~~4) **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 logical tones in the assigned 802.16e sub-channels.

~~4)~~5) **Cyclic tone shift:** The final step consists of introducing a cyclic shift of $L = (m-1)\ .\ (N_U/M)$ tones~~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 correlates the 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.

Remarks

a) Note that the amount of cyclic shift ~~may be greater than 1 tone from antenna to antenna~~is set to the maximal valuein this case, although a shift of 1 works well in most cases. In general, the optimum cyclic shift must be determined by simulation for different rates and MIMO configurations. The maximum cyclic shift is equal to ~~$N_{DS}$~~ $N_U$ /$M$, where $N_U$~~$_{DS}$~~ = number of data tones ~~that 1 FEC block is mapped to~~assigned to a user.

b) 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).

c) This interleaver applies to spatial streams with ABL (adaptive bit loading) as well. Bits are multiplexed as per step 2 in the interleaver. As the lower modulation order symbols fill up, remaining bits are placed on higher modulation symbols. Details of adaptive bit loading are further described in [6].

~~An example of SF-BICM with a cyclic shift of 1 tone is provided below.~~

**~~Example C: Proposed SF-BICM for 2 transmit antennas on 802.16e FUSC DL: 1 sub-channel, 1 FEC block, 48 data tones, rate _ QPSK~~**

```
~~2 BITS per QPSK symbol mapped to transmit antenna #1~~
~~  Columns 1 through 14~~
~~     1     65    129      3     67    131      5     69    133      7     71    135      9     73~~
~~    33     97    161     35     99    163     37    101    165     39    103    167     41    105~~
~~  Columns 15 through 28~~
~~   137     11     75    139     13     77    141     15     79    143     17     81    145     19~~
~~   169     43    107    171     45    109    173     47    111    175     49    113    177     51~~
~~  Columns 29 through 42~~
~~    83    147     21     85    149     23     87    151     25     89    153     27     91    155~~
~~   115    179     53    117    181     55    119    183     57    121    185     59    123    187~~
~~  Columns 43 through 48~~
~~    29     93    157     31     95    159~~
```

~~61 125 189 63 127 191~~

~~Shift of 1 tone from antenna 1 to 2~~

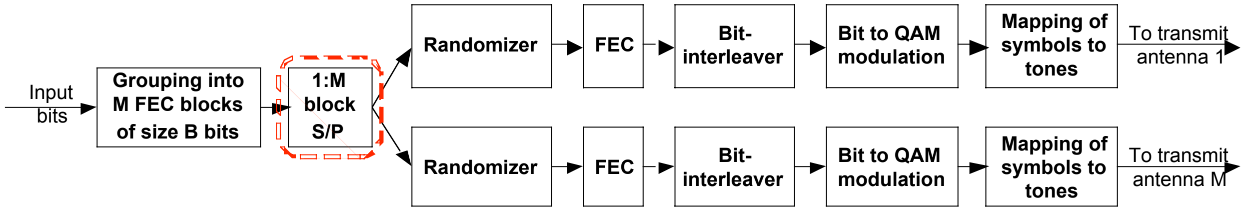
~~2 BITS per QPSK symbol mapped to transmit antenna #2~~
~~Columns 1 through 14~~
~~160 **2** 66 130 **4** 68 132 6 70 134 8 72 136 10~~
~~192 34 98 162 36 100 164 38 102 166 40 104 168 42~~
~~Columns 15 through 28~~
~~74 138 12 76 140 14 78 142 16 80 144 18 82 146~~
~~106 170 44 108 172 46 110 174 48 112 176 50 114 178~~
~~Columns 29 through 42~~
~~20 84 148 22 86 150 24 88 152 26 90 154 28 92~~
~~52 116 180 54 118 182 56 120 184 58 122 186 60 124~~
~~Columns 43 through 48~~
~~156 30 94 158 32 96~~
~~188 62 126 190 64 128~~

~~Columns of BITS on both antennas above are mapped to the following TONES (same as SISO)~~
~~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~~

# 4 Simulation Results

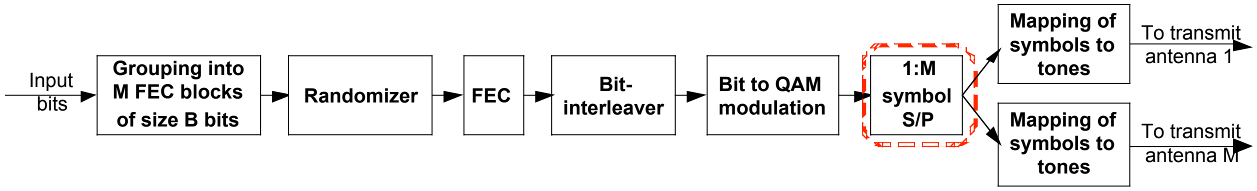
This section demonstrates performance of the proposed SF-BICM over 2x2 MIMO systems in PUSC mode with 1024-point FFT. The 2x2 MIMO architecture transmits 2 spatial streams, one on each transmit antenna, and uses an MMSE receiver to recover them. Performance is tested on ITU pedestrian channel model A with a low rms delay spread of 45 ns, and the Pedestrian model B with a high rms delay spread of 750 ns, at a Doppler spread corresponding 3 km/h. The frequency selective channels on each transmit-receive antenna pair are i.i.d. Packet error rate is computed for 200 byte packets. Two data rates are considered: rate _ QPSK and rate _ 16-QAM. We assume perfect channel estimation, phase and carrier tracking and symbol synchronization, and floating point precision.

Performance of three schemes is shown in Figure 6: (1) the proposed SF-BICM labeled "- -h Bit Intlv", (2) simple spatial multiplexing labeled "x-No Intlv" (or horizontally encoded streams) and illustrated in Figure 4, and (3) a simpler symbol interleaver labeled "-0-Sym Intlv" (example vertical interleaver structure) and illustrated in Figure 5.



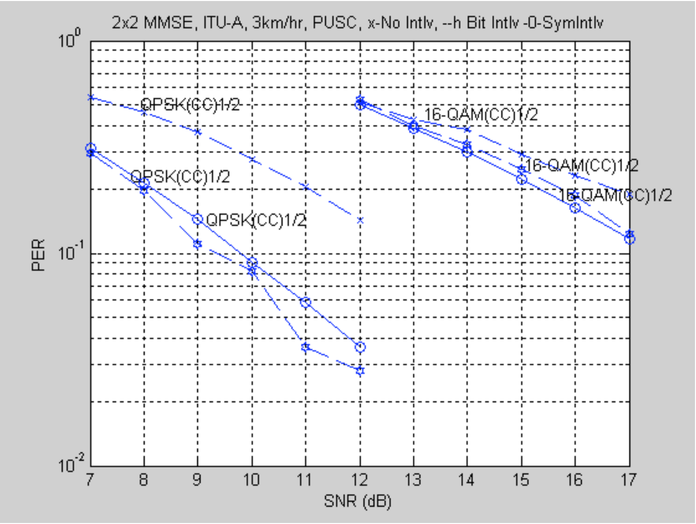
**~~Figur~~Figure 4~~e 4~~: Simple spatial multiplexing of FEC blocks on multiple antennas**

The block interleaver takes consecutive blocks of B bits and multiplexes them to different antennas. Therefore bits on different transmit antennas are independent. On each antenna, 802.16e interleaving is followed. This method (F-BICM)is expected to provide frequency diversity but no spatial diversity.



**~~Figure 5~~Figure 5: Symbol interleaving on multiple antennas**

The symbol interleaver multiplexes consecutive coded QAM symbols on different antennas. This method is expected to provide some frequency diversity and some spatial diversity.



**~~Figure 6~~Figure 6 (a): SF-BICM vs BICM over low delay spread**

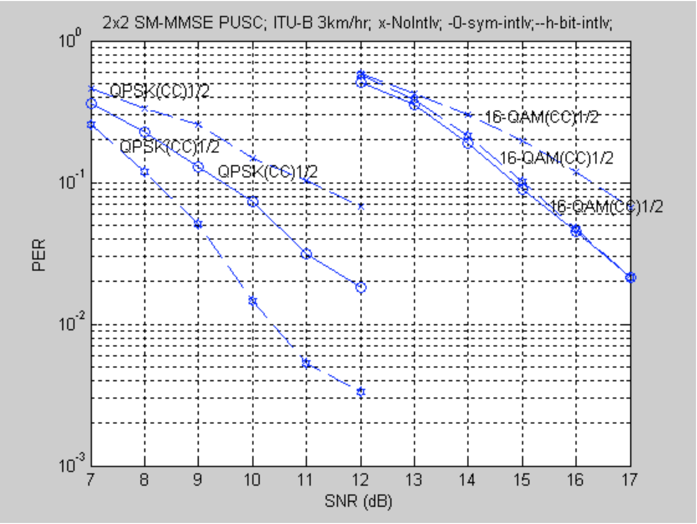


**Figure 6(b): SF-BICM vs BICM over high delay spread**

In Figures 6(a) and 6(b), the slopes of MIMO+SFI are sharper than those of MIMO+SM, suggesting better diversity. Performance of symbol interleaving lies in between SF-BICM and F-BICM. With higher frequency diversity in 6(b), SF-BICM outperforms F-BICM by 3 db at PER 10%. SF-BICM provides a higher gain for lower data rates, extending the connectivity and cell range. The MMSE receiver induces correlation across antennas because of cross-talk, and the channel induces correlation across tones because of limited delay spread. Together these two factors induce correlation among adjacent tones on all antennas. Our proposed interleaver places bits on uncorrelated tones and antennas as much as possible, thereby improving performance with the MMSE receiver. The minimal shift of 1 tone was used in the above results.

Additional results are shown for the case of FUSC/PUSC comparison using small packet sizes. A packet size of 12 bytes is chosen here to focus on the spatial interleaving gains. Figure 7~~Figure 7~~ and Figure 8~~Figure 8~~ compare the SF-BICM and BICM schemes for the FUSC/PUSC permutation in the ITUA-3 km/hr channel. A gain of 1-3 dB of SF-BICM vs BICM is still noted in this case.

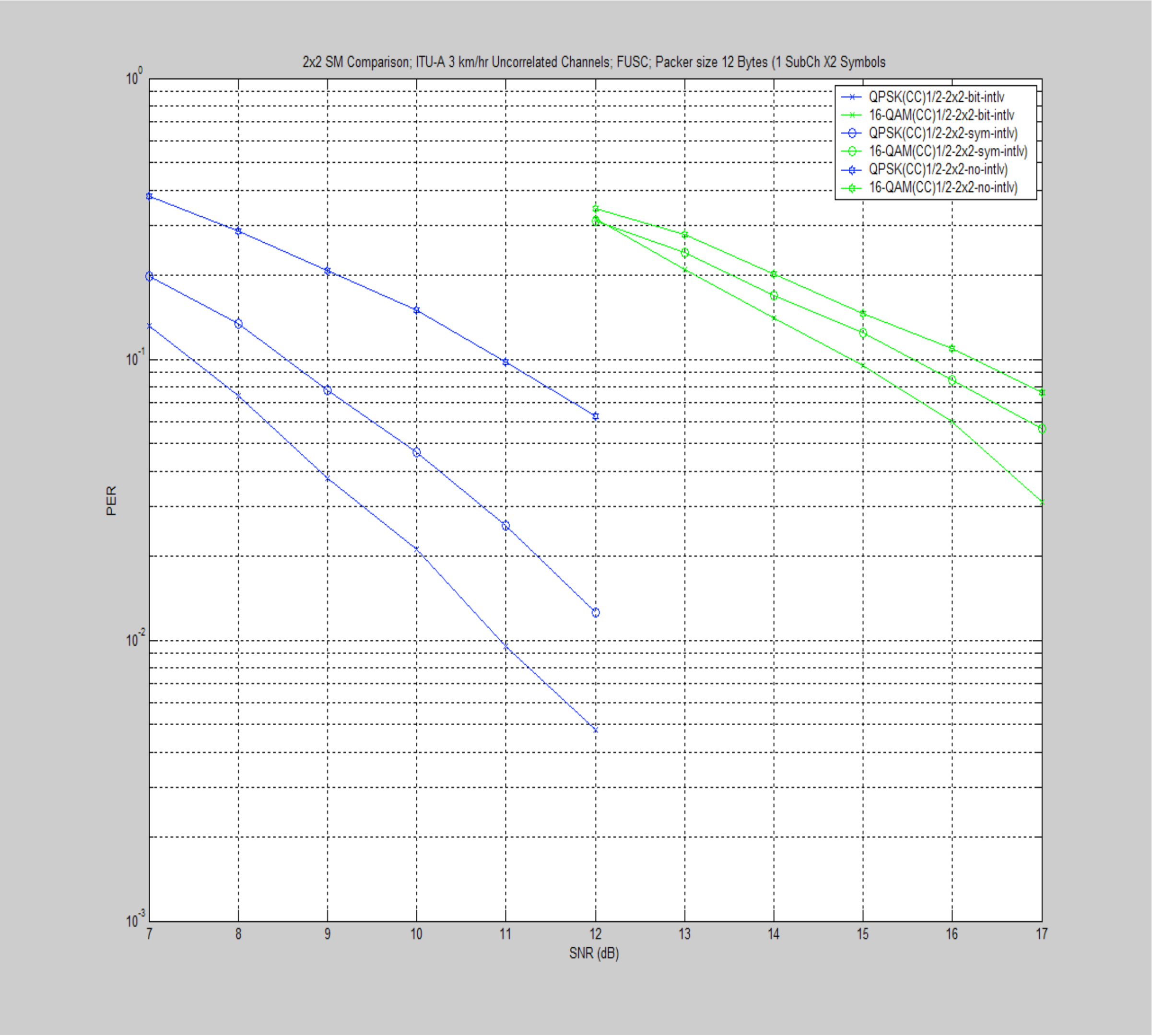


**Figure 7: SF-BICM vs BICM for FUSC over ITU-A 3 km/hr channels.**

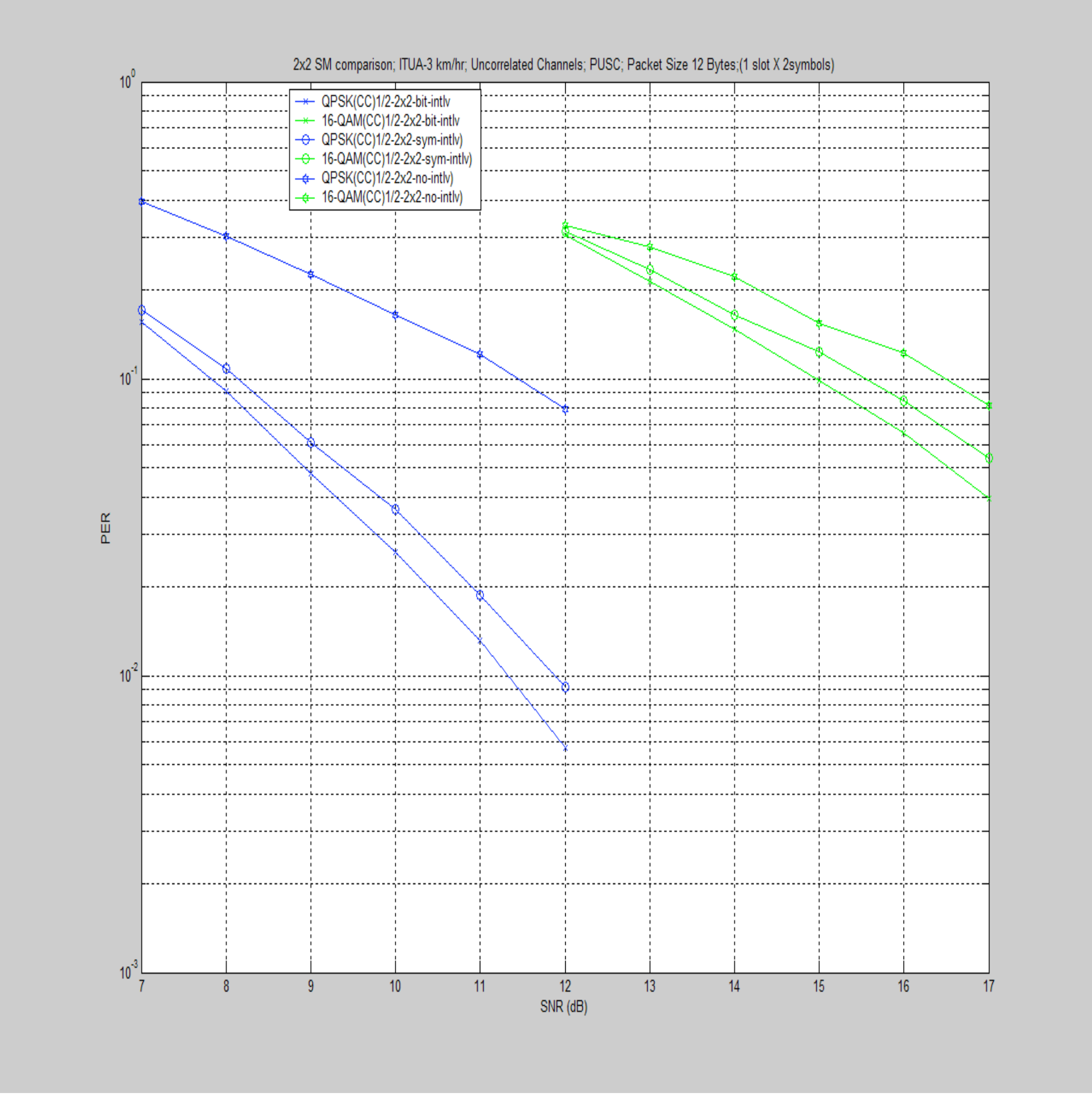


**Figure 8~~898~~ SF-BICM vs BICM for PUSC permutation over ITU-A 3k/hr channels.**

# 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/D5a, December 2004.
[4] H. Heiskala and J. Terry, OFDM Wireless LANs: A Theoretical and Practical Guide, SAMS, 2002.
[5] ITU channel models reference
[6] Q. Li et. al , “Clarification on vertically encoded MIMO,” ~~Q. Li et. al ,~~ IEEE C802.16e-05/52r5, Jan. 2005.~~3~~