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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** |
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| Re: | |
| Abstract | One of the smart antenna options in the 802.16e standard is multiple-input, multiple-output (MIMO) systems. MIMO requires multiple antennas at both the transmitter and receiver. Multiple transmit antennas can be used in diversity mode to provide greater range or in spatial multiplexing mode to provide higher throughput. 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. 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.<br><br>In this contribution we propose space-frequency bit-interleaved coded modulation (SF-BICM) which interleaves FEC blocks across both spatial streams and frequency tones. Spatial streams are multiple data streams transmitted over multiple antennas, with or without some form of spatial pre-coding such as beamforming, covariance weighting or singular value decomposition. 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. |
| Purpose | Adoption of proposed changes into P802.16e<br>~~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

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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. 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.

## 2 Proposed text change

***[Add a new section 8.4.8.10 as follows]***

### 8.4.8.10 Space-frequency bit-interleaved coded modulation (SF-BICM)

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

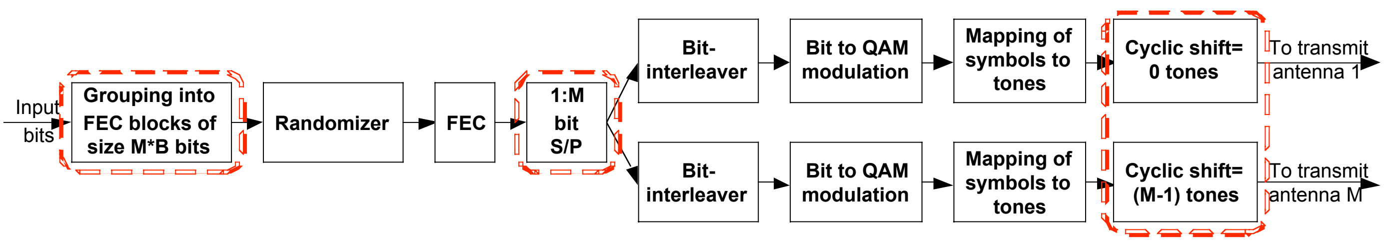


**Figure 1: Space-frequency bit-interleaved coded modulation (SF-BICM)**

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.

SF-BICM TRANSMITTER

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

   The following steps apply to each FEC block.

2) **Serial to parallel multiplexing:** 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 $N_{DS}$ 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 $m-1$ tones to the right.

SF-BICM RECEIVER

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 $m-1$ 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 $MN_{CBPS}$ bits.
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 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.

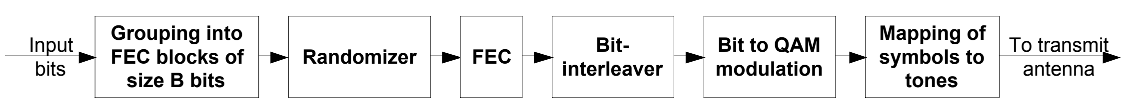


**Figure 2: IEEE 802.16e mapping of uncoded bits to OFDM tones on a single antenna**

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.

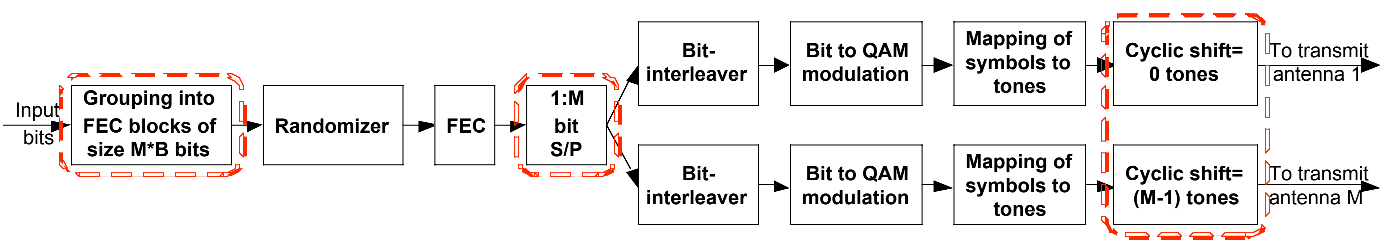


**Figure 3: Proposed SF-BICM mapping of bits to multiple antennas (or spatial streams)**

1) **FEC encoding:** Group the incoming uncoded bits into blocks of size *MB*, such that the coded output blocks are of size $MN_{CBPS}$. 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.

2) **Serial to parallel antenna multiplexing:** 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) **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 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, 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 $N_{DS}/M$, where $N_{DS}$ = number of data tones that 1 FEC block is mapped to.
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.

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" and illustrated in Figure 4, and (3) a simpler symbol interleaver labeled "-0-Sym Intlv" and illustrated in Figure 5.

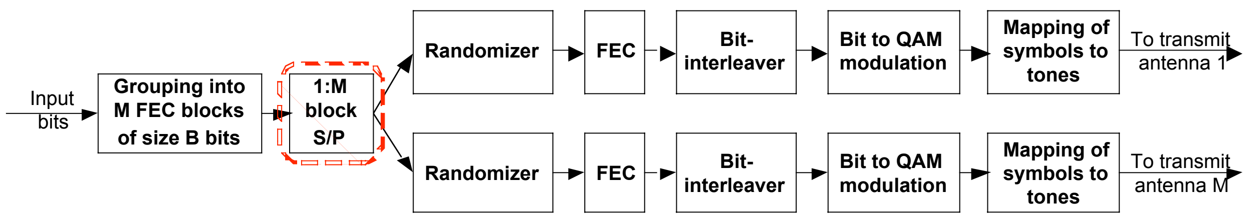


**Figure 4: Simple spatial multiplexing of FEC blocks on multiple antennas**

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.

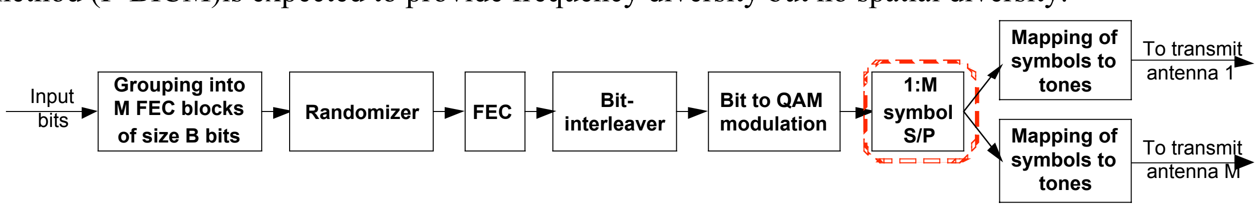


**Figure 5: Symbol interleaving on multiple antennas**

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

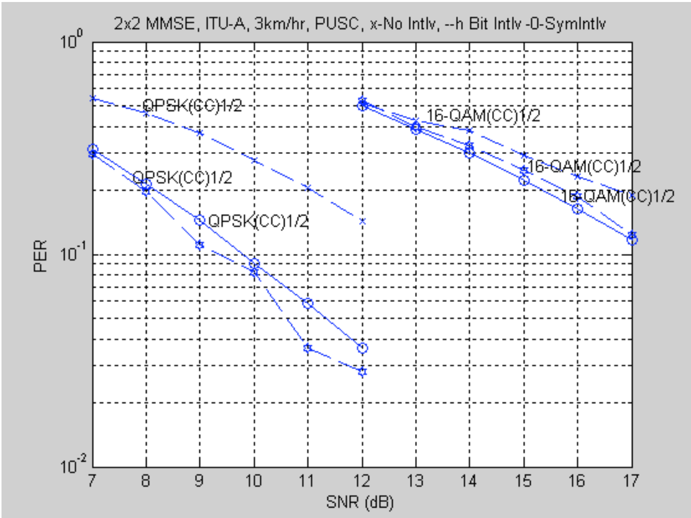


Figure 6(a): SF-BICM vs BICM over low delay spread

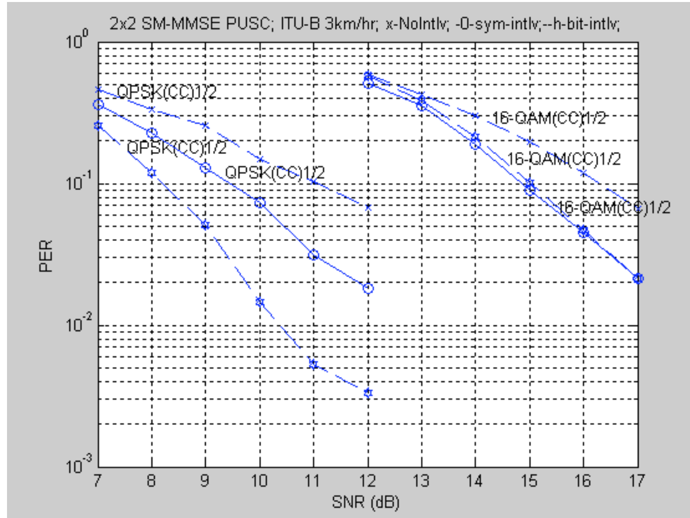


**Figure 6(b): SF-BICM vs BICM over high delay spread**

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.

## Acknowledgments

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