Preamble-based SNR Estimation Algorithm for Wireless MIMO OFDM Systems

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***Abstract*—Orthogonal frequency division multiplexing (OFDM) offers high data rates and robust performance in frequency selective channels by link adaptation utilizing information about the channel quality. Combined with multiple-input multiple-output (MIMO) technique it provides improved link reliability and increased data rate. A crucial parameter required for adaptive transmission is the signal-to-noise ratio (SNR). In this paper, we propose a novel SNR estimation algorithm for wireless 2×2 MIMO OFDM systems based on the reuse of the synchronization preamble. The periodic structure of the preamble is utilized for the computationally efficient estimation of average SNR and SNRs per subcarrier, based on the second-order moments of received preamble samples. The performance of the proposed algorithm is assessed for channels with different levels of frequency selectivity. Simulation results show robust performance of proposed algorithm even in strong frequency selective channels.**

I. Introduction

OFDM is a multicarrier modulation scheme that provides strong robustness against intersymbol interference (ISI) by dividing the broadband channel into many narrowband subchannels in such a way that attenuation across each subchannel stays flat. Orthogonalization of subchannels is performed with low complexity by using the fast Fourier transform (FFT). The serial high-rate data stream is converted into multiple parallel low-rate streams, each modulated on a different subcarrier.

To further increase the transmission rate without increasing signal bandwidth, the use of multiple antennas, called multiple-input multiple-output (MIMO) technique, has also recently received large attentions. MIMO offers additional parallel channels in spatial domain providing improved link reliability and increased data rate through multiplexing technique. Hence, MIMO OFDM systems offer a promising combination for the high data requirement of present (WiMAX, WLAN) and future wireless systems.

An important task in the design of future MIMO OFDM system is to exploit frequency selective channels by adaptable transmission parameters (bandwidth, coding/data rate, power) to preserve power and bandwidth efficiency according to channel conditions at the receiver. In order to achieve such improvements, efficient and exact signal-to-noise ratio (SNR) estimation algorithm is required. The SNR is defined as the ratio of the desired signal power to the noise power and is widely used as a standard measure of signal quality for communication systems. SNR estimators derive estimate by averaging the observable properties of the received signal over a number of symbols. Prior to SNR per subcarrier estimation for adaptive transmission, the average SNR and channel frequency response have to be estimated.

There are two general categories of average SNR estimators. *Data-aided* (DA) estimators are based on either perfect or estimated knowledge of the transmitted data. However, a certain portion of data is needed for estimation purposes, which reduces bandwidth efficiency. Blind or *in-service* estimators operate on unknown information-bearing portion of the received signal preserving efficiency at the cost of decreased performance. For packet based communications, block of information data is usually preceded by several training symbols (preambles) of known data used for synchronization and equalization purposes. Therefore, DA SNR estimators can utilize preambles without additional throughput reduction.

Most of the SNR estimators proposed in the literature so far are related to single carrier single-input single-output (SISO) transmission. In [1], a detailed comparison of various algorithms is presented. Most of these algorithms can be directly applied to SISO OFDM systems in additive white Gaussian noise (AWGN) [2], while the SNR estimation in frequency selective channels additionally requires efficient estimation of channel state information (CSI). To the best of our knowledge only Boumard in [3] proposed preamble-based SNR estimation algorithm for 2×2 MIMO OFDM systems.

In [4], we proposed an efficient and robust algorithm, named PS estimator, for SNR estimation in frequency selective time-invariant SISO OFDM systems. The PS estimator utilizes preamble structure, proposed by Morelli and Mengali in [5]. Compared to Schmidl and Cox synchronization method [6], it allows synchronization over a wider frequency offset range with only one preamble, hence reducing the training symbol overhead. Since the proposed estimation algorithm relies on the signal samples at the output of the FFT, its performance depends strongly on the given preamble structure.

In this paper, we extend our previous work by proposing modification of PS estimator for 2×2 MIMO OFDM systems, named MIMO-PS estimator. Proposed estimator uses one preamble allowing better bandwidth efficiency compared to

This work has been partially supported by the UMIC Research Center, RWTH Aachen University.

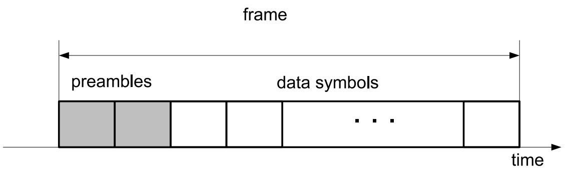

Fig. 1. Frame structure

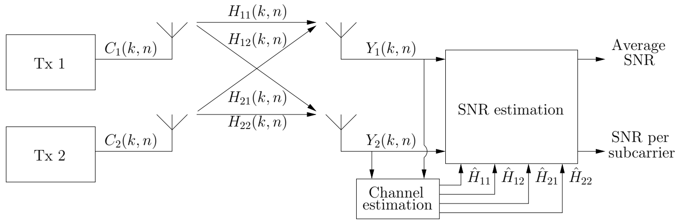

Fig. 2. Simplified block diagram of 2×2 MIMO OFDM system

Boumard's estimator which inherently uses two preambles.

The remainder of this paper is organized as follows. Section II provides the system model and specifies the SNR estimation problem. The MIMO-PS estimator is described in Section III. Its performance is analyzed by computer simulations in Section IV. Finally, some concluding remarks are given.

II. System Model

In many wireless OFDM systems, transmission is normally organized in frames. Typical frame structure is shown in Fig. 1 where sequence of data symbols is preceded by several preambles of known data used for the synchronization and/or channel estimation purposes. We consider general model of frame structure composed of K preambles where each preamble contains N modulated subcarriers. Accordingly, simplified block diagram of considered 2×2 MIMO OFDM system in the acquisition mode is shown in Fig. 2. Since we consider SNR estimation performed in frequency domain, given model contains only frequency domain characterization of received signal in frequency selective AWGN channels. Let $C_i(k,n)$ denote the complex data symbol on nth subcarrier in kth preamble at ith transmit antenna, where $k = 0, \ldots, K-1$, $n = 0, \ldots, N-1$ and $i = 1, 2$. It is assumed that modulated subcarrier has unit magnitude, i.e. $|C_i(k,n)|^2 = 1$, which is a regular assumption since present OFDM standards usually contain preambles composed of QPSK and/or BPSK modulated subcarriers. At the receiver, perfect synchronization is assumed, hence after FFT, received signal on nth subcarrier in kth preamble at jth receive antenna can be expressed as

$$Y_j(k,n) = \sqrt{\frac{S}{2}} \sum_{i=1}^{2} C_i(k,n) H_{ij}(k,n) + \sqrt{W_j}\eta_j(k,n), \quad (1)$$

where $j = 1, 2$, $S/2$ is the transmitted signal power at single antenna (giving the total transmit power of S), $\eta_j(k,n)$ and W_j are sampled complex zero-mean AWGN of unit variance and noise power at receiving antenna j, respectively, and $H_{ij}(k,n)$ is the channel frequency response between ith and jth antenna given by

$$H_{ij}(k,n) = \sum_{l=1}^{L} h_{l,ij}(kT_s) \cdot e^{-j2\pi \frac{n\tau_{l,ij}}{NT_s}}. \quad (2)$$

Here, $h_{l,ij}(kT_s)$ and $\tau_{l,ij}$ denote the lth path gain and delay between ith and jth antenna during the kth preamble, respectively, T_s is the duration of the OFDM preamble and L is the memory length of the channel. The channel path gains $h_{l,ij}(kT_s)$ are uncorrelated and normalized for each pair of Tx/Rx antennae so that their expected total power is unity, i.e. $\sum_{l=1}^{L} |h_{l,ij}(kT_s)|^2 = 1$ is satisfied for $\forall\, i, j$.

Our initial assumption is that channel is constant during the whole frame, since we consider SNR estimation algorithms for the purposes of adaptive transmission. Therefore, the time index k is omitted during the estimation procedure, i.e. $H_{ij}(k,n)$ is replaced by $H_{ij}(n)$. It is also assumed that average SNR and SNR per subcarrier estimates are valid for all information data bearing OFDM symbols within the frame. As it is shown in [3], the received signal average SNR can be expressed as

$$\begin{aligned} \rho_{av} &= \frac{1}{2} \sum_{j=1}^{2} \frac{\sum_{i=1}^{2} E\{\sum_{n=0}^{N-1} |\sqrt{\frac{S}{2}} C_i(k,n) H_{ij}(n)|^2\}}{E\{\sum_{n=0}^{N-1} |\sqrt{W_j}\eta_j(k,n)|^2\}} \\ &= \frac{S}{4} \sum_{j=1}^{2} \frac{\sum_{i=1}^{2} \sum_{n=0}^{N-1} |H_{ij}(n)|^2}{W_j} \\ &= \frac{1}{2} \sum_{j=1}^{2} \frac{S}{W_j} = \frac{1}{2} \sum_{j=1}^{2} \rho_{av,j}, \end{aligned} \quad (3)$$

where $\rho_{av,j} = S/W_j$ is the average SNR at jth antenna and $\sum_{n=0}^{N-1} |H_{ij}(n)|^2 = N$, is satisfied. In the case of equal noise power at antennae, i.e. $W_1 = W_2 = W$, the average SNR can be expressed as $\rho_{av} = \frac{S}{W}$.

Furthermore, the SNR on the nth subcarrier is given by

$$\begin{aligned} \rho(n) &= \frac{1}{2} \sum_{j=1}^{2} \frac{\sum_{i=1}^{2} E\{|\sqrt{\frac{S}{2}} C_i(k,n) H_{ij}(n)|^2\}}{E\{|\sqrt{W_j}\eta_j(k,n)|^2} \} \\ &= \frac{S}{4} \sum_{j=1}^{2} \frac{\sum_{i=1}^{2} |H_{ij}(n)|^2}{W_j} \\ &= \frac{1}{4} \sum_{j=1}^{2} \rho_{av,j} \sum_{i=1}^{2} |H_{ij}(n)|^2. \end{aligned} \quad (4)$$

From (4), it is clear that SNR per subcarrier estimate depends on average SNR (or average noise) estimate at each antenna and appropriate channel estimates.

III. Proposed Estimator

A new estimator based on periodically used subcarriers is explored in this section, named MIMO-PS estimator in the following. The key idea rests upon the time domain periodic preamble structure for time and frequency synchronization proposed in [6]. In order to cover a wider frequency range, in [5] a preamble of Q identical parts, each containing N/Q samples is proposed as depicted in Fig. 3a and Fig. 3c.

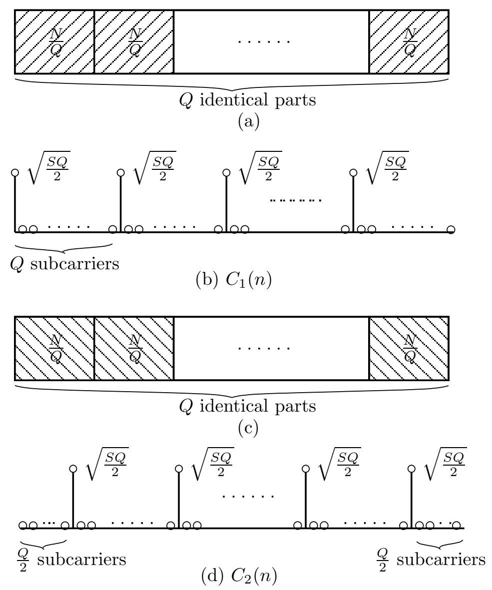

Fig. 3. Preamble structure in a), c) time and b), d) frequency domain

The corresponding frequency domain representation for the preamble transmitted from 1st and 2nd antenna is shown in Fig. 3b and Fig. 3d, respectively. In the sequel we assume that Q divides N, so that $N_p = N/Q$ is integer.

Starting from the 0th and $\frac{Q}{2}$th subcarrier, at 1st and 2nd antenna, respectively, each Qth subcarrier is modulated with a QPSK signal $C_{i_p}(m_i)$ with $|C_{i_p}(m_i)| = 1$, $i = 1, 2$. For $m = 0, 1, \dots, N_p - 1$, indexes of loaded subcarriers at the 1st and 2nd antenna are given as $m_1 = mQ$ and $m_2 = (m + \frac{1}{2})Q$, respectively. The remainder of $N_z = N - N_p = \frac{(Q-1)}{Q}N$ subcarriers at each antenna is not used (nulled), giving the $\frac{(Q-2)}{Q}N$ subcarriers which are nulled on both antennae. In order to maintain the total energy level over all symbols within the preamble, the power is additionally scaled by factor Q yielding a total transmit power of $\frac{SQ}{2}$ on loaded subcarriers.

Write $n = mQ + q$, $m = 0, \dots, N_p - 1$, $q = 0, \dots, Q - 1$. The transmitted signal on the nth subcarrier at the 1st and 2nd antenna is written as

$$C_1(n) = C_1(mQ+q) = \begin{cases} C_{1_p}(m_1), & q = 0 \\ 0, & q \neq 0 \end{cases} \tag{5}$$

and

$$C_2(n) = C_2(mQ+q) = \begin{cases} C_{2_p}(m_2), & q = \frac{Q}{2} \\ 0, & q \neq \frac{Q}{2} \end{cases}, \tag{6}$$

respectively. By (1) the received signal on the nth subcarrier at jth antenna is given by

$$Y_j(n) = Y(mQ+q) = \begin{cases} Y_{1j_p}(m_1), & q = 0 \\ Y_{2j_p}(m_2), & q = \frac{Q}{2} \\ Y_{j_z}(mQ+q), & q \neq \left\{0, \frac{Q}{2}\right\} \end{cases},$$

where

$$Y_{ij_p}(m_i) = \sqrt{\frac{SQ}{2}}\, C_{i_p}(m_i) H_{ij_p}(m_i) + \sqrt{W_j}\,\eta_{j_p}(m_i) \tag{7}$$

denote the received signal on loaded subcarriers, and

$$Y_{j_z}(mQ+q) = \sqrt{W_j}\,\eta_{j_z}(mQ+q) \tag{8}$$

the received signal on nulled subcarriers containing only noise.

The empirical second-order moment of received signal on loaded subcarriers is

$$\hat{M}_{2,ij_p} = \frac{1}{N_p}\sum_{m_i} |Y_{ij_p}(m_i)|^2. \tag{9}$$

Its expected value is given as

$$\begin{aligned} E\left\{\hat{M}_{2,ij_p}\right\} &= \frac{1}{N_p}\sum_{m_i} E\left\{|Y_{ij_p}(m_i)|^2\right\} \\ &= \frac{QS}{2N_p}\sum_{m_i} E\left\{|H_{ij_p}(m_i)|^2\right\} + \frac{W_j}{N_p}\sum_{m_i} E\left\{|\eta_{j_p}(m_i)|^2\right\} \\ &= \frac{QS}{2} + W_j. \end{aligned}$$

Similarly, the empirical second moment of the received signal on nulled subcarriers,

$$\hat{M}_{2,j_z} = \frac{1}{N_p(Q-2)} \sum_{m=0}^{N_p-1} \sum_{\substack{q=1 \\ q\neq \frac{Q}{2}}}^{Q-1} |Y_{j_z}(mQ+q)|^2, \tag{10}$$

has expectation

$$\begin{aligned} E\left\{\hat{M}_{2,j_z}\right\} &= \frac{1}{N_p(Q-2)} \sum_{m=0}^{N_p-1} \sum_{\substack{q=1 \\ q\neq \frac{Q}{2}}}^{Q-1} E\left\{|Y_{j_z}(mQ+q)|^2\right\} \\ &= \frac{W_j}{N_p(Q-2)} \sum_{m=0}^{N_p-1} \sum_{\substack{q=1 \\ q\neq \frac{Q}{2}}}^{Q-1} E\left\{|\eta_{j_z}(mQ+q)|^2\right\} \\ &= W_j. \end{aligned}$$

In summary, the average SNR at jth antenna $\rho_{av,j}$ can be estimated by forming

$$\begin{aligned} \hat{\rho}_{av,j} &= \frac{1}{Q}\frac{\left(\sum_{i=1}^{2} \hat{M}_{2,ij_p} - 2\hat{M}_{2,j_z}\right)}{\hat{M}_{2,j_z}} \\ &= \frac{1}{Q}\left((Q-2)\frac{\sum_{i=1}^{2}\sum_{m_i} |Y_{ij_p}(m_i)|^2}{\sum_{m=0}^{N_p-1}\sum_{\substack{q=1 \\ q\neq \frac{Q}{2}}}^{Q-1} |Y_{j_z}(mQ+q)|^2} - 2\right), \end{aligned} \tag{11}$$

where, by the strong law of large numbers, $\hat{M}_{2,ij_p}$ and $\hat{M}_{2,j_z}$ are strongly consistent unbiased estimators of $\frac{QS}{2} + W_j$ and average noise power W_j at jth antenna, respectively. In the case of equal noise power on antennae, i.e. $W_1 = W_2 = W$, average SNR estimate can be expressed as

$$\begin{aligned} \hat{\rho}_{av} &= \frac{1}{Q}\frac{\left(\sum_{j=1}^{2}\sum_{i=1}^{2} \hat{M}_{2,ij_p} - 2\sum_{j=1}^{2}\hat{M}_{2,j_z}\right)}{\sum_{j=1}^{2}\hat{M}_{2,j_z}} \\ &= \frac{1}{Q}\left((Q-2)\frac{\sum_{j=1}^{2}\sum_{i=1}^{2}\sum_{m_i} |Y_{ij_p}(m_i)|^2}{\sum_{j=1}^{2}\sum_{m=0}^{N_p-1}\sum_{\substack{q=1 \\ q\neq \frac{Q}{2}}}^{Q-1} |Y_{j_z}(mQ+q)|^2} - 2\right). \end{aligned}$$

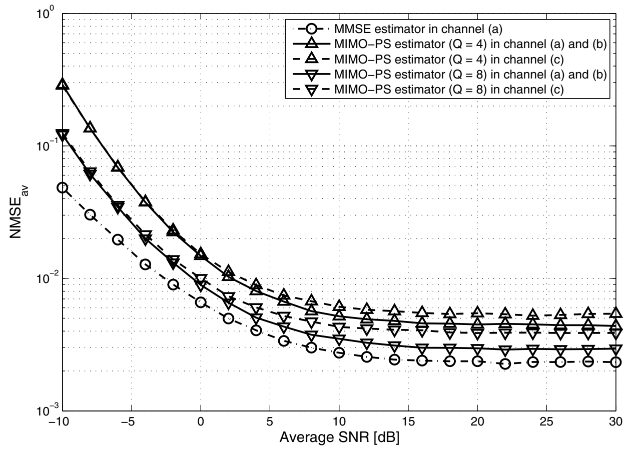

Fig. 4. NMSE of the average SNR estimation based on one preamble

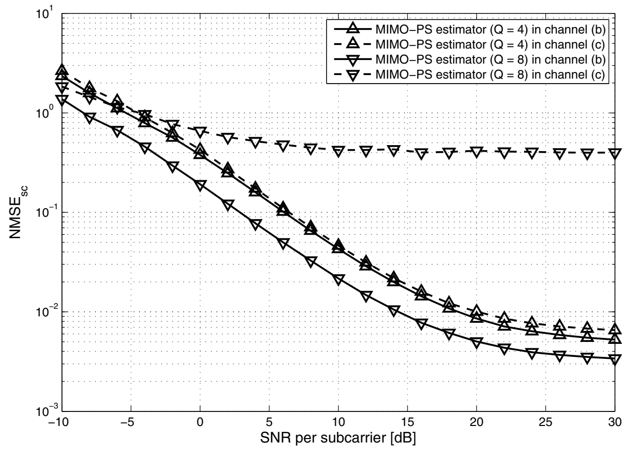

Fig. 5. NMSE of the SNR per subcarrier estimation based on one preamble

Note that the PS estimator does not need any knowledge of the transmitted symbols or channel estimates on loaded subcarriers for the purpose of average SNR estimation. Only the arrangement of loaded and nulled subcarriers must be known to the receiver. However, channel estimates are requisite for the estimation of SNRs per subcarrier (4). Since they are available only for the loaded subcarriers by the means of least squares (LS) estimation as

$$\begin{aligned}\hat{H}_{ij_p}(m_i) &= C^*_{i_p}(m_i)Y_{ij_p}(m_i)\\ &= \sqrt{\frac{SQ}{2}}\,H_{ij_p}(m_i) + \sqrt{W_j}\,C^*_{i_p}(m_i)\eta_{j_p}(m_i),\end{aligned} \tag{12}$$

the rest of $\hat{H}_{ij_z}(mQ+q)$, $m = 0,\ldots,N_p-1$, $q = 1,\ldots,-\frac{Q}{2},\frac{Q}{2},\ldots,Q-1$ on nulled subcarriers can be obtained by linear or DFT based interpolation, see [7]. Furthermore, SNR estimate on nth subcarrier can be written as (4)

$$\hat{\rho}(n) = \frac{1}{2}\sum_{j=1}^{2}\frac{\sum_{i=1}^{2}|\hat{H}_{ij}(n)|^2}{\hat{M}_{2,j_z}}. \tag{13}$$

It can be easily noticed that increasing the number of periodic parts Q gives more nulled subcarriers which can influence the estimator performance (13) in two distinct ways. According to (10), average noise power estimates become more accurate since there are more samples available for estimation. On the other side, decreased number of LS estimates available on loaded subcarriers (12) introduces performance degradation due to interpolation over increased number of nulled subcarriers. However, degrading interpolation effect is partially compensated since power on each loaded subcarriers is scaled by factor Q as it is shown in Fig. 3. Proposed estimator can be further extended for arbitrary MIMO systems with N_{T_x} transmit and N_{R_x} receive antennae. A single design condition that has to be fulfilled is that the number of subcarriers which are nulled on each receive antennae must be larger or equal to $N/2$, i.e. $Q \geq 2N_{T_x}$.

TABLE I
PARAMETERS FOR MULTIPATH CHANNELS (B) AND (C)

Channel	(b)	(c)
Tap 1 delay (samples)	0	0
Tap 1 power (dB)	-4.52, Ricean factor = 1	-1.92
Tap 2 delay (samples)	3	12
Tap 2 power (dB)	-6.51	-5.92
Tap 3 delay (samples)	7	32
Tap 3 power (dB)	-11.51	-9.92

IV. SIMULATION RESULTS

The performance of MIMO PS estimator is evaluated by the means of Monte-Carlo simulation. OFDM system parameters used in the simulation are taken from WiMAX specifications giving $N = 256$ subcarriers and cyclic prefix length of 32 samples. Performance is evaluated for three different channels: (a) AWGN channel, (b) a 3-tap time-invariant fading channel with a root mean square delay spread $\tau_{rms} = 2$ samples and (c) a 3-tap time-invariant fading channel with a $\tau_{rms} = 10$ samples. Parameters for considered channels are taken from [3], whose details are given in Table I. The number of independent trials is set to $N_t = 100000$ assuring the high confidence interval of the estimates. The evaluation of the performance is done in terms of normalized MSE (NMSE) of the estimated average SNR values following

$$\text{NMSE}_{\text{av}} = \frac{1}{N_t}\sum_{i=1}^{N_t}\left(\frac{\hat{\rho}_{av,i}-\rho_{av}}{\rho_{av}}\right)^2, \tag{14}$$

where $\hat{\rho}_{av,i}$ is the estimate of the average SNR in the ith trial, and ρ_{av} is the true value. Furthermore, the NMSE of the estimated SNRs per subcarrier is given by

$$\text{NMSE}_{\text{sc}} = \frac{1}{NN_t}\sum_{i=1}^{N_t}\sum_{n=0}^{N-1}\left(\frac{\hat{\rho}(n)_i-\rho(n)}{\rho(n)}\right)^2, \tag{15}$$

where $\hat{\rho}(n)_i$ is the estimate of the $\rho(n)$ in the ith trial. During the simulation, MIMO-PS estimator is evaluated for two different cases of preamble's repeated parts, i.e. $Q = 4$ and 8. Also, in order to compare its performance with Boumard's estimator, under the same spectral efficiency conditions, a

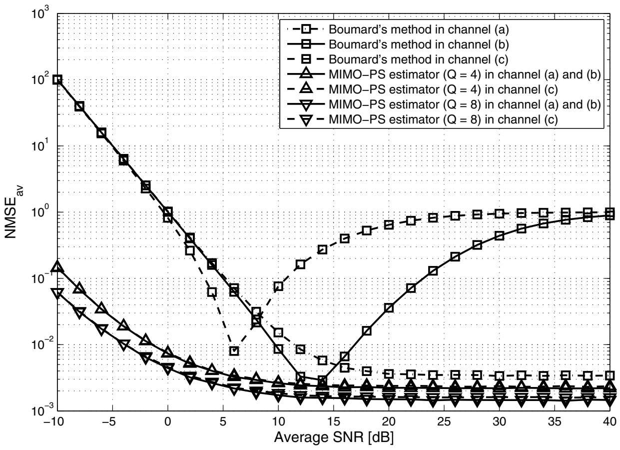

Fig. 6. NMSE of the average SNR estimation based on two preambles

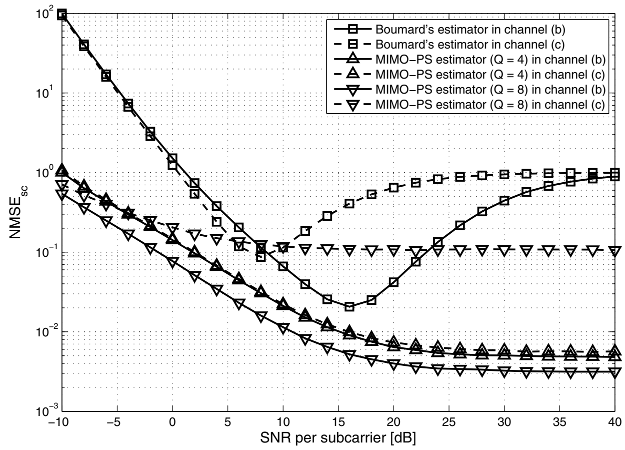

Fig. 7. NMSE of the SNR per subcarrier estimation based on two preambles

version of MIMO-PS estimator based on two preambles is also examined. Preamble structure shown in Fig. 3 can be extended by adding the 2nd preamble at each antenna with interchanged loaded subcarrier arrangement present at 1st preambles. Therefore, SNR estimates at each antenna can be obtained by averaging over two preambles giving the improved performance as it is shown in Fig. 6 and Fig. 7.

Fig. 4 shows the NMSE_{av} of MIMO-PS estimator based on one preamble in considered channels. The appropriate performance of Minimum Mean Square Error (MMSE) estimator, an optimal estimator in AWGN channel [2], is shown for reference. It can be seen that MIMO-PS estimator performs the same in channels (a) and (b), which correspond to AWGN and moderate frequency selective channel, respectively. Note that the increase of the number of identical parts Q brings its performance closer to MMSE estimator. It can be explained with the notion that more subcarriers are used for the average noise power estimation (10) while at the same time transmitted power on loaded subcarriers is scaled by Q, giving the more accurate estimate in (9). However, the performance of MIMO-PS estimator become slightly worse for the strong frequency selective channel (c).

Similar behavior of NMSE_{sc} is shown in Fig. 5. Additionally, it can be seen that SNR per subcarrier MIMO-PS estimator stops to benefit from the increase of Q in strong frequency selective channels due to degrading influence of the interpolation over nulled subcarriers.

Fig. 6 compares the NMSE_{av} of MIMO-PS estimator based on two preambles with Boumard's estimator. For the same Q, curves become indistinguishable for various channels. Therefore, MIMO-PS estimator shows robust behavior even in strong frequency selective channel, due to averaging over two preambles, and performs better than Boumard's estimator which is strongly affected by the channel selectivity since it inherently assumes that channel coefficients are the same on adjacent subcarriers [3]. However, NMSE_{sc} of MIMO-PS estimator based on two preambles stays affected by strong frequency selectivity for $Q = 8$, as shown in Fig. 7.

Performance can be further improved by combining estimated average noise power with more sophisticated channel estimation algorithms using pilot subcarriers within the data symbols, which can be the subject of further investigation.

V. Conclusion

In this paper, a preamble-based SNR estimation algorithm for wireless 2×2 MIMO OFDM systems has been proposed. Reuse of the synchronization preamble for the SNR estimation purposes by exploiting its time domain periodic structure puts no additional overhead on transmitted OFDM frame. Preamble structure was appropriately adopted for MIMO OFDM systems offering additional robustness. Increasing the number of repeated parts by nulling the subcarriers on specified positions improves the performance of considered estimator, but also increases its sensitivity to frequency selectivity. Low complexity and robustness to frequency selectivity combined with the bandwidth efficiency favors the proposed estimator compared to the existed preamble-based estimators given in the literature. Further performance analysis for MIMO systems with arbitrary dimensions could give insight into possible limitations of proposed algorithm.

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