Spatial, Spectral and Temporal Adaptation for Fast Fading MIMO-OFDMA Systems

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Abstract—**Modern wireless communication systems are designed to operate in diverse propagation conditions. Adaptive transmission techniques are powerful tools for achieving this objective. We propose a new adaptive transmission method for fast fading channels. The new method combines benefits of closed loop and open loop transmission techniques by efficient utilization of resources in time, frequency and spatial domains. In the new approach we consider how to allocate different MIMO schemes and alternative subchannelization methods in a given frame depending on the mobile speed, number of antennas and signal-to-noise ratio (SNR). Numerical results show effectiveness of the proposed method for a wide range of mobile speeds.**

I. Introduction

In designing wireless communication systems, efficient utilization of bandwidth resources is very crucial. In MIMO-OFDMA based communication systems, these resources are in time, frequency and spatial domains. If the channel knowledge is not available at the transmitter, *open loop* (OL) transmission techniques are employed which distribute bandwidth resources uniformly in frequency and spatial domains to achieve diversity gain in the channel. On the other hand, if channel knowledge can be acquired at the transmitter with a reasonable cost, then MIMO transmission method can be adapted to changing channel conditions in order to obtain power gain in spatial domain and the channel can be adaptively assigned to the desired user to obtain multiuser diversity gain in the frequency domain. These methods are termed *closed loop* (CL) transmission techniques.

In OFDMA system, as adjacent subcarriers experience almost the same channel gain, channelization or resource partitioning among users can be based on groups of contiguous subcarriers known as resource blocks (RBs). The channel gains on the subcarriers within an RB can be considered to be the same. Although an RB can be defined over several OFDM symbols, in this paper we define it over one OFDM symbol to allow adaptation for fast fading channel. These RBs are divided into subchannels to be allocated to users. Subchannel structure is designed according to the desired operating conditions to take advantage of underlying channel characteristics. If the channel is slow fading, then channel information can be obtained at the transmitter with sufficient reliability. In this case, consecutive subcarriers are grouped together in frequency domain to form band-type subchannels. This structure allows implementation of CL transmission techniques. When the channel is fast fading, it is usually assumed that acquiring channel knowledge at the transmitter is not feasible. In this scenario, the subchannels are formed from subcarriers distributed in the available spectrum which can be termed as interleaved-type subchannels. Interleaved-type subchannel structure is suitable for OL transmission techniques.

It can be shown that neither CL nor OL transmission is optimum in certain scenarios between very fast fading and slow fading channels. Therefore the transmission scheme and the subchannel structure should be carefully designed to consider the operating conditions of the system. [1]-[2] study optimum MIMO transmission scheme when the channel is not perfectly known at the transmitter. In [3]-[5], authors propose multiple antenna transmission schemes robust to channel knowledge imperfections which combines benefits of beamforming and space diversity techniques. In [6]-[7], resource allocation for OFDMA systems is studied when the channel knowledge is imperfect at the transmitter. In all of these works, channel imperfection is considered to be a constant value in a frame duration. This model is suitable for channel perturbations due to feedback delays, quantization errors or channel estimation errors. In fast fading channels, the channel can change within a frame duration. This fast fading channel can be observed in mobile speeds that are supported by next generation cellular wireless standards [13]-[15]. In such fading conditions, even if the initial channel knowledge is reliable in the beginning of the frame, it will become outdated in later part of the frame. Considering this fast fading channel, we recently proposed a transmission scheme that allocates beamforming (BF) and space frequency coding (SFC) schemes depending on the time selectivity of the channel [9] and an evolving subchannel structure that incorporates band-type and interleaved-type structures to accommodate different mobile speeds in SISO systems [8]. The former considered spatial and temporal adaptation within each frame while the latter addressed spectral and temporal adaptation.

In this work, we propose an adaptive transmission strategy for fast fading channels in which both

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user channelization and MIMO transmission mode are adapted in a given frame. Although the new user subchannel structure is not static within the frame, it just needs to be designed offline once. On the other hand, MIMO transmission mode adaptation is performed based on the initial channel knowledge in each frame. Taking advantage of both OL and CL transmissions, the proposed method performs better than individual transmission methods in all mobile speeds.

The rest of the paper is organized is as follows. The system and channel model are introduced in Section II. In Section III, the proposed method is explained. Performance of the proposed method is demonstrated with numerical simulations in Section IV and the paper is concluded in Section V.

II. System Model

In this paper, we consider downlink (DL) of a wireless network employing OFDMA as multiple access method. Base station (BS) is equipped with n_t antennas and each mobile user has single receive antenna, i.e. $n_r = 1$ [1]. The received signal of user k on subcarrier q at symbol time n is given by

$$y_q^k(n) = \mathbf{h}_{q,n}^k \mathbf{x}_q^k(n) + w_q^k(n) \tag{1}$$

where $w_q^k(n)$ is the noise which is complex Gaussian distributed with zero mean and unit variance. $\mathbf{h}_q^k(n)$ is the $1 \times n_t$ vector containing channel coefficients of user k on subcarrier q. It is assumed that the channels are statistically independent and identically distributed (iid) between different users. Each channel coefficient is distributed as complex Gaussian with zero mean and unit variance. $\mathbf{x}_q^k$ is the transmitted signal vector for user k on the subcarrier q with average power $\mathrm{E}[\|\mathbf{x}_q^k(n)\|^2] = \eta$, therefore η is the average SNR on each subcarrier per receive antenna.

A. Channel Model

The channel is fast fading. We assume that quasi-static fading assumption is not valid in a frame level but the OFDM subcarrier spacing is properly chosen to avoid inter-carrier interference such that the channel stays essentially the same during one OFDM symbol duration. The transmitter can obtain the channel knowledge either through uplink measurements for TDD systems or with feedback from the receiver for FDD systems. In either case, our analysis focuses on channel knowledge imperfections at the transmitter due to the time selectivity of the channel. Channel vector at symbol time n, $\mathbf{h}_{q,n}^k$ is given by

$$\mathbf{h}_{q,n}^k = \rho_n \mathbf{h}_{q,0}^k + \sqrt{1-\rho_n^2}\,\mathbf{h}_{e,q,n}^k \tag{2}$$

[1]In this paper we are concerned about how to utilize channel knowledge at the transmitter for single stream transmission. In this case, finding optimum combining weights at the receiver is trivial. Also, the performance for $n_r > 1$ shows a similar trend to the case of $n_r = 1$. Therefore, we consider single receive antenna case in this work to simplify the analysis.

where $\mathbf{h}_{q,0}^k$ is the channel knowledge available at the beginning of the frame and $\mathbf{h}_{e,q,n}^k$ is the perturbation term due to decorrelation effect. ρ_n is the correlation coefficient between the initial channel knowledge $\mathbf{h}_{q,0}^k$ and current channel realization $\mathbf{h}_{q,n}^k$ at symbol time n. Although channel is changing during a frame, the receiver can estimate the channel with pilot tones inserted into the frame in time-frequency grid. Thus, in this work we assume that the receiver has perfect channel knowledge for all decoding purposes. In the following analysis we adopt a channel with uniform power delay profile with independent taps. Although this assumption is necessary for the analysis, other power delay profiles can be accommodated by finding degrees of freedom in the frequency selective channel.

B. Alternative Subchannelization Methods

We consider an OFDM modulated system with Discrete-Fourier-Transform (DFT) size N_{dft}, out of which N_{used} of them are used. Available spectrum is divided into N_{subchan} subchannels and each subchannel is constructed from N_{rb} RBs, each consisting of N_{scrb} subcarriers. Therefore, $N_{\mathrm{used}} = N_{\mathrm{subchan}} \times N_{\mathrm{rb}} \times N_{\mathrm{scrb}}$. Subchannels are formed by grouping N_{rbchan} resource blocks. Permutation of the resource blocks in a given subchannel results in different subchannelization (user channelization) structures. In this paper, we consider two different reference subchannelization methods as depicted in Figure 1. First, consecutive resource blocks are grouped to form subchannels, which is called band-type subchannelization. Second, subchannels are constructed from resource blocks which are non-adjacently distributed in the frequency domain. This approach is called interleaved-type subchannelization. The third subchannelization structure shown in Figure 1 is related to the proposed transmission approach in this work and will be explained in the following.

III. Proposed Transmission Method

In this work, we propose a practical transmission strategy for fast fading channels. In the new approach we jointly consider adapting multiple antenna transmission scheme and subchannel structure. The proposed method is designed to improve reliability, i.e. bit-error-rate (BER) for a fixed transmission rate. Benefits of OL and CL methods are utilized by allocating alternative transmission methods in a given frame depending on the time-selectivity of the channel and SNR. We choose beamforming (BF) and space-frequency coding (SFC) as alternative multiple antenna techniques. First the channel structure is determined based on the desired operating point which is determined by average SNR and mobile speed. Then, BF and SFC is allocated in a frame based on initial channel knowledge. In the sequel, we look into approximate BER performance metrics of

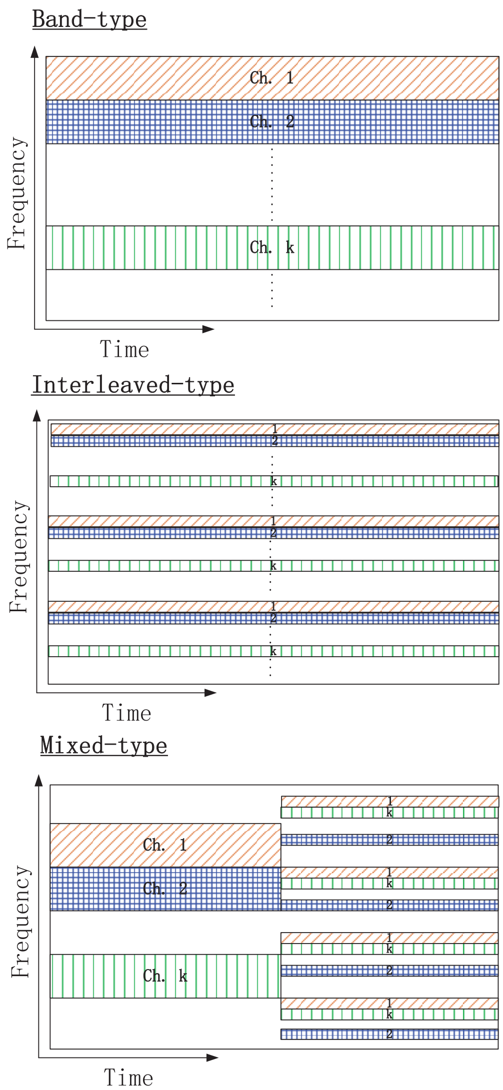

Fig. 1. Alternative subchannel structures

alternative transmission methods with different channelization structures. By knowing these metrics, we propose adaptive subchannelization and MIMO mode allocation algorithm. Approximate BER expressions are derived for M-QAM modulated signal. The approximation $P_b(\gamma) \approx 0.2e^{-\frac{1.5\gamma}{M-1}}$ from [10] is used in the analysis where γ is the SNR per symbol. For the fading channel, the average BER performance can be obtained from

$$P_b \approx 0.2 \int_0^\infty e^{-\frac{1.5\gamma}{M-1}} f_\gamma(\gamma) d\gamma \tag{3}$$

where $f_\gamma(\gamma)$ is probability density function (PDF) of the effective SNR.

A. BER of BF with Alternative Subchannel Structures

If perfect channel knowledge is available at the transmitter, adaptive channel selection and BF provide power gain in addition to the diversity gain that can be obtained with OL systems. When the initial channel knowledge is acquired at the transmitter, the subchannel with the highest gain is selected and beamforming vector coefficients are calculated for this subchannel. However, this initial channel knowledge becomes outdated throughout the frame when the channel is fast fading. Therefore benefits of CL transmission decreases towards the end of the frame. In state of the art systems, CL transmission is avoided if channel does not stay static at least for a frame duration. In this work, we show that benefits of CL transmission can be partially obtained when the user channelization structure is carefully designed. For this purpose, we first start by deriving approximate BER performance of BF with alternative subchannel structures when channel is following the fast fading channel model in (2).

Following analysis focuses on a given user that is assigned to its best channel. Hence, we omit user index for clarity. The transmitter calculates beamforming coefficients $\mathbf{v}_q$ for the given subcarrier q with the initial channel knowledge $\mathbf{h}_{q,0}$ at the beginning of the frame as $\mathbf{v}_q = \mathbf{h}_{q,0}^H / \|\mathbf{h}_{q,0}\|$. The received signal is then given by

$$y_q(n) = \mathbf{h}_{q,n}\mathbf{v}_q x_q(n) + w_q(n) \tag{4}$$

where $x_q(n)$ is the transmitted symbol and $w_q(n)$ is the AWGN noise. Note that the received SNR is given by $\gamma_{q,n} = \eta \|\mathbf{h}_{q,n}\mathbf{v}_q\|^2$. According to the channel model in (2), the random variable $z_{q,n} = \sqrt{\eta}\mathbf{h}_{q,n}\mathbf{v}_q$ is given by

$$\begin{aligned} z_{q,n} &= \sqrt{\eta}(\rho_n \mathbf{h}_{q,0} + \sqrt{1-\rho_n^2}\mathbf{h}_{q,n}^e)\mathbf{v}_q \\ &= \sqrt{\eta}(\rho_n \|\mathbf{h}_{q,0}\| + \sqrt{1-\rho_n^2} h_{q,n}^e) \end{aligned} \tag{5}$$

where $h_{q,n}^e = \mathbf{h}_{q,n}^e \mathbf{v}_q$. SNR on subcarrier q at symbol time n is given by $\gamma_{q,n} = |z_{q,n}|^2$. Note that SNR at the symbol time $n = 0$ is $\gamma_{q,0} = \eta \|\mathbf{h}_{q,0}\|^2$.

We implement bit level interleaving and coding in time-frequency grid to capture time and frequency diversity of the system. It is difficult to obtain closed form performance metrics for an arbitrary coding method. For simplicity of analysis we derive BER metrics based on repetition coding in frequency domain. When different coding schemes are applied, a correction coefficient should be introduced to the effective SNR. The effective SNR is given by

$$\gamma_n = \beta \sum_{q=l_1}^{l_Q} \gamma_{q,n}, \tag{6}$$

where $l_1, \ldots, l_Q$ are the subcarrier indices in the given subchannel and β is the correction factor. Since the channel is highly correlated in consecutive subcarriers, effective SNR in (6) simplifies to $\gamma_n = Q\beta\gamma_n^*$ for band-type subchannel where γ_n^* is the SNR in the subcarrier which is located in the middle of the given subchannel. Conditioned on the initial channel knowledge $\mathbf{h}_{q,0}$, $z_{q,n}$

is a complex Gaussian distributed random variable with mean $\rho_n\sqrt{\eta}\|\mathbf{h}_0\|$ and variance $\eta(1-\rho_n^2)$. Therefore it is easy to see that γ_n is a noncentral Chi-square random variable with 2 degrees of freedom and noncentrality parameter $s=\rho_n\sqrt{\eta\beta Q}\|\mathbf{h}_0\|$. PDF of SNR at symbol time n for a given channel knowledge $\mathbf{h}_0$ can be expressed as

$$\begin{aligned} f_{\gamma_n|\gamma_0}(\gamma_n|\gamma_0) &= \frac{1}{\eta\beta Q(1-\rho_n^2)}\exp\left(-\frac{\rho_n^2\gamma_0+\gamma_n}{\eta\beta Q(1-\rho_n^2)}\right) \\ &\times\ I_0\left(\frac{2\rho_n}{\eta\beta Q(1-\rho_n^2)}\sqrt{\gamma_n\gamma_0}\right) \end{aligned}$$

where $I_m(.)$ is the m-th order modified Bessel function of the first kind. Average BER performance for M-QAM at symbol n conditioned on the current channel realization $\mathbf{h}_0$ as can be easily derived using the BER approximation in (3) as

$$\begin{aligned} P_b^{\mathrm{BF-band}}(n,M_n,\gamma_0) &\approx 0.2\left(\frac{3(1-\rho_n^2)\eta Q\beta}{2(M_n-1)}+1\right)^{-1} \\ &\times\exp\left(-\frac{3\rho_n^2\gamma_0}{3(1-\rho_n^2)\eta Q\beta+2(M_n-1)}\right). \end{aligned} \tag{7}$$

If the subchannel structure is interleaved-type, coding across frequency efficiently captures diversity in the frequency selective channel. Therefore the effective SNR as expressed in (6) is a Chi-square random variable with $2d_f$ degrees of freedom, where d_f is the frequency diversity order. Following similar steps to arrive at (7), average BER metric for the BF scheme in an interleaved-type subchannel is given as

$$\begin{aligned} P_b^{\mathrm{BF-int}}(n,M_n,\gamma_0) &\approx 0.2\left(\frac{3(1-\rho_n^2)\eta\beta}{2(M_n-1)d_f}+1\right)^{-d_f} \\ &\times\exp\left(-\frac{3\rho_n^2\gamma_0 d_f}{3(1-\rho_n^2)\eta\beta+2(M_n-1)d_f}\right) \end{aligned} \tag{8}$$

where $d_f=\min(L,Q)$ and L is the number of independent time domain taps of the channel.

B. BER of SFC with Alternative Subchannel Structures

If channel knowledge cannot be obtained with sufficient reliability, diversity techniques are implemented to extract degrees of freedom in the system. Since the transmitter does not know the channel, the best approach is to distribute transmission power uniformly in all dimensions as much as possible. In this study, we choose space frequency block coding (SFBC) as spatial diversity technique due to its simple decoding method. In SFBC, a block of m modulated symbols are coded across n_f subcarriers and coded vectors are simultaneously transmitted from n_t antennas. Rate of such a SFBC is $R=m/n_f$. In this paper, we optimize transmission mode to minimize BER for a fixed rate and fixed power transmission. If the rate of SFBC is $R<1$, then modulation order of SFBC should be increased to satisfy constant rate requirement. Considering the system model in (1), we can write the received signal on symbol time n and subcarrier q as

$$y_q(n)=\mathbf{h}_{q,n}\mathbf{x}_q(n)+\mathbf{w}_q(n) \tag{9}$$

where $\mathbf{x}_q(n)$ is $n_t\times 1$ transmitted signal vector generated according to a given SFBC matrix. As the channel is highly correlated across consecutive subcarriers, receiver can decode symbols with linear complexity. Symbols from each antenna are normalized by $1/\sqrt{n_t}$ to satisfy constant power requirement, i.e., $E[\|\mathbf{x}_q(n)\|^2]=\eta$. Thus, the received SNR on subcarrier q is given by $\gamma_{q,n}=a\frac{\eta}{n_t}\|\mathbf{h}_{q,n}\|_F^2$ [12], where a is a parameter that is a function of SFBC code. $a=1$ for Alamouti code and $a=2$ for rate 1/2 code designed for 4 transmit antennas. Encoding across frequency extracts frequency diversity of the channel. When a band-type channel structure is employed together with SFBC transmission, it captures multiuser diversity gain from the adaptive channel selection and diversity gain in the spatial domain. Following the steps to arrive at (7), we can easily obtain average BER metric of SFBC transmission on band-type subchannel structure as

$$\begin{aligned} P_b^{\mathrm{SFC-band}}(n,M_n,\gamma_0) &\approx 0.2\left(\frac{3a(1-\rho_n^2)\eta Q\beta}{2(M_n-1)n_t}+1\right)^{-n_t} \\ &\times\exp\left(-\frac{3\rho_n^2\gamma_0 n_t}{3a(1-\rho_n^2)\eta Q\beta+2(M_n-1)n_t}\right). \end{aligned} \tag{10}$$

SFBC when used with interleaved-type subchannel provides diversity in spatial and frequency domain. Remembering that the diversity order of the frequency selective channel is d_f, it can be noted that γ_n now is a central Chi-square distributed random variable with $2n_td_f$ degrees of freedom. PDF of SNR conditioned on the initial channel knowledge can be written as

$$f_\gamma(\gamma)=\frac{n_td_f}{a\eta\Gamma(n_td_f)}\gamma^{n_td_f-1}\exp\left(-\frac{n_td_f}{a\eta}\gamma\right),$$

where $\gamma()$ is the Gamma function. The average BER performance of SFC transmission with interleaved-type subchannel structure can be written as

$$P_b^{\mathrm{SFC-int}}(\eta,M_n)\approx 0.2\left(1+\frac{1.5a}{d_fn_t(M_n-1)}\eta\right)^{-n_td_f}. \tag{11}$$

Since this transmission mode does not utilize channel knowledge for adaptive channel selection or beamforming, performance is independent of symbol index n.

C. Adaptive Transmission Mode and Subchannel Allocation

In the new method, we propose to adapt subchannel structure as well as multiple antenna transmission scheme to changing channel conditions. The transmission mode is adapted as a function of initial channel knowledge, modulation order, SNR and time correlation properties of the channel. It should be noted that it may not be practical to have different subchannel structures in different portions of the OFDMA frame. Therefore it is better to determine subchannel structure based on unconditional BER performance rather than conditioned on the channel knowledge.

In the proposed method, we follow a two step approach for transmission adaptation. First, the subchannel structure is designed offline for a given average SNR η and mobile speed. This decision is based on unconditional BER performance of completely CL (BF with band-type subchannel) and OL (SFC with interleaved-type subchannel) transmissions. The same subchannel structure is maintained in a given frame for all users. Second, multiple antenna schemes are allocated in each frame with conditional BER metrics obtained in (7),(8),(10) and (11). Therefore, multiple antenna schemes can vary between different users.

The first step requires knowledge of unconditional BER performance metrics. As explained in the previous section, performance of OL transmission in (11) is already an unconditional BER metric. Due to the space limitations, we cannot include unconditional BER performance of BF with band-type subchannel structure here, but it is available in [9].

Once the subchannel structure is fixed, (7),(8),(10) and (11) are used to estimate switching points inside the frame to allocate different transmission modes as

$$m^*(n) = \underset{m(n)}{\arg\min}\ P_b^m(n, M_n, \gamma_0)$$

where $m^*(n)$ is the transmission mode index on symbol n and $m(n) \in$ {BF-band, BF-int, SFC-band, SFC-int}. Power gain due to adaptive channel selection and beamforming is still observed in the beginning of the frame. As the channel knowledge becomes outdated at later part of the frame, these gains can drop below performance of OL scheme. When it occurs, the proposed scheme switches to the open loop scheme. Note that the transmission mode selection for each symbol of a frame is done on a frame by frame basis.

IV. Simulations and Results

In this section we demonstrate the performance of the proposed transmission method with numerical simulations. Channel coefficients are independent identically distributed between different antennas and they are generated according to the Jakes's model [11], where $\rho_n = J_0(2\pi f_d T_s n)$ with T_s being the OFDM symbol duration and f_d being the Doppler frequency. In our simulations, $f_c = 2$ GHz and $T_s = 71.35$ μs.

DFT size is 1024, where out of 1024 subcarriers, 576 of them are used as in LTE. Three different subchannelization methods are used in the simulations. For $n_t = 2$, used subcarriers are grouped into 144 RBs each consisting of 4 consecutive subcarriers. Each subchannel is allocated 6 RBs. For $n_t = 4$, used subcarriers are grouped into 72 RBs each consisting of 8 consecutive subcarriers. Each subchannel has 3 RBs. RB for 4 antennas uses more adjacent subcarriers because the SFBC encodes 4 symbols over 8 subcarriers. Subchannels are formed from consecutive RBs for band-type structure and from distributed RBs for interleaved-type structure. The subchannel structure of the proposed approach is a mixture of the two as shown in Figure 1. Number of OFDM symbols in each frame is taken as 14 and 28 for different simulations.

It is assumed that the receiver has perfect channel knowledge throughout the frame and the transmitter obtains channel knowledge at the beginning of the frame without feedback delay[2]. When performing BF in a subchannel, BF vector are computed for each subcarrier. When implementing SFBC, full rate Alamouti code is used for $n_t = 2$, however rate $1/2$ code is used if $n_t = 4$. Therefore, the modulation order of BF, M_{CL} , is equal to the modulation order of SFBC, M_{OL}, when $n_t = 2$, whereas $M_{\mathrm{OL}} = M_{\mathrm{CL}}^2$ when $n_t = 4$ to maintain the same data rate. The information is encoded with rate $1/2$ convolutional code with constraint length of 7. Correction coefficient of $\beta = 0.5$ is chosen to account for differences between the repetition code used in the analysis and the convolutional code in the simulations.

In Figures 2 and 3, performances of individual OL and CL transmissions and proposed transmission method are shown. The average SNR is 15dB for $n_t = 2$ and 8 dB for $n_t = 4$. It can be seen that performance of OL transmission improves while the performance of CL transmission degrades with increasing mobile speed. The proposed method is seen to perform better than both schemes in all mobile speeds.

Figures 4 and 5 demonstrate the performance for a fixed mobile speed of 200km/h for $n_t = 2$ and 250km/h for $n_t = 4$. It is again seen that the proposed method has a performance gain over individual schemes.

V. Conclusions

A novel approach of spatial, spectral and temporal adaptation is proposed for fast fading channels in which both user channelization and MIMO transmission modes are adapted in a given frame. The user channelization is designed based on average SNR and mobile speed. On the other hand, MIMO transmission mode is adapted on frame-by-frame basis as a function of initial channel knowledge. Taking advantage of both OL and CL transmissions, the proposed method performs better than individual transmission methods in wide range of mobile speeds.

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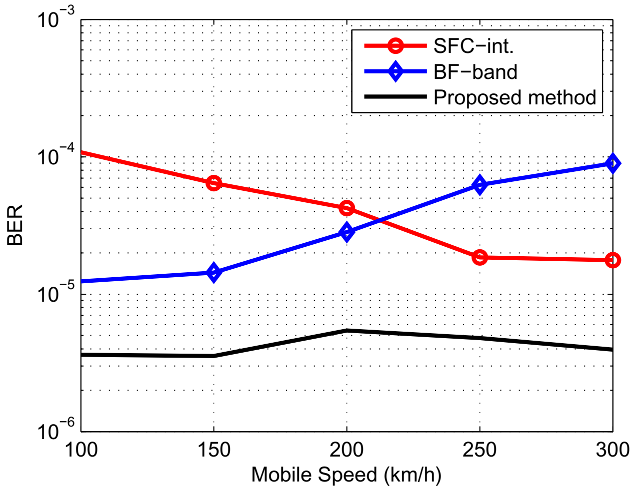

Fig. 2. BER performance for 16-QAM modulation with rate 1/2 convolutional code, n_t=2, n_r=1, SNR=15dB.

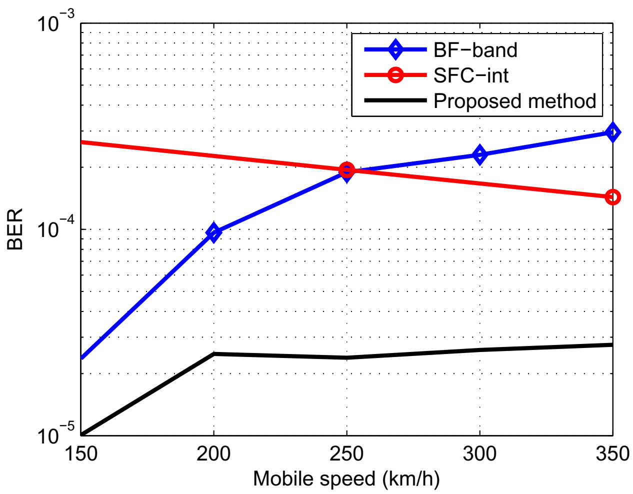

Fig. 3. BER performance for 16-QAM modulation with rate 1/2 convolutional code, n_t=4, n_r=1, SNR=8dB.

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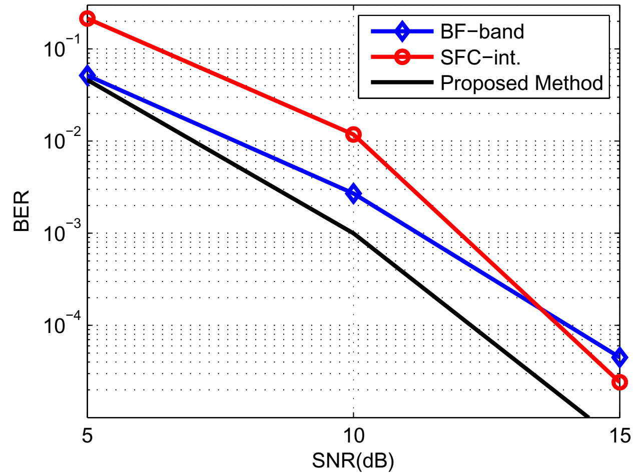

Fig. 4. BER performance for 16-QAM modulation with rate 1/2 convolutional code, n_t=2, n_r=1, mobile speed=200km/h.

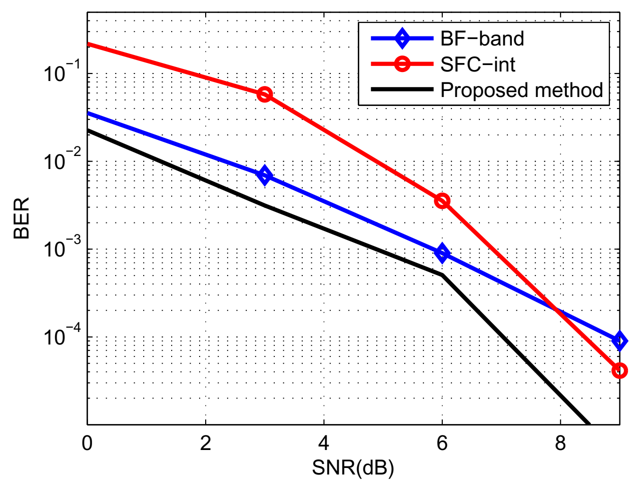

Fig. 5. BER performance for 16-QAM modulation with rate 1/2 convolutional code, n_t=4, n_r=1, mobile speed=250km/h.

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