Multi-User Detection for Asynchronous Space-Frequency Block Coded Schemes in Frequency Selective Environments

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Abstract—**Multi-user detection is an efficient approach proposed to boost the spectral efficiency of a wireless communication system. While multi-user detection in synchronous systems or in flat fading environments has been successfully addressed, it is still an open and challenging problem in the practical case of asynchronous MIMO systems employing space-frequency (time) block coding and operating in frequency selective environments. In this paper, we show how the concept of multi-user detection can be efficiently extended to the latter case with a low complexity overhead and a small performance loss compared to the synchronous case.**

I. INTRODUCTION

Dealing with frequency selective channels is a major challenge in wideband digital communication systems. To simplify the receiver structure, frequency domain equalization solutions such as OFDM are adopted. These techniques cope with frequency selectivity without the need for complex time-domain equalizers. Furthermore, simple flat fading channels realized in frequency domain facilitate the utilization of space-time coding and other MIMO techniques [1], [2] thereby improving the spectral efficiency and throughput of wireless transmission. There are two popular approaches for exploiting diversity in a MIMO-OFDM system. They are namely space-time coding over each subcarrier, i.e., space-time frequency coding; and substituting different time slots with different subcarriers, i.e., space-frequency coding [3].

To further boost spectral efficiency in multi-user wireless systems, multi-user detection techniques incorporating MIMO are proposed. Examples of such methods include the MU-MIMO for 3GPP long term evolution (LTE) [4] and collaborative MIMO for WiMax [5]. However, the synchronization of distributed users is a serious challenge in a multiuser wireless communication system. On one hand, frequency synchronization may be manageable in a static network, for example with a base station in a cellular setting, since all mobile users need to compensate against their static frequency offset. On the other hand and for a dynamic network, high resolution time synchronization in MAC is not achievable given the fact that it demands a high signaling overhead. To that end, solutions such as timing advance (TA) can be utilized in scheduled networks to synchronize uplink transmissions to some extent [4]. Establishing synchronization in a random access network such as IEEE 802.11 [6] is more challenging considering the distributed nature of such networks and the high cost of signaling overhead.

In this work, we introduce a methodology to enable multiple-user detection in an asynchronous MIMO space-frequency coded system with frequency selective channels. To the best of our knowledge, this is the first low overhead technique for space-frequency coded multi-user detection in frequency selective channels. Existing methods in the literature are either designed for flat fading channels [7], or designed for single antenna users [4], [5] ignoring space-frequency (time) coding in multiple-user transmissions.

The idea of detecting two Alamouti coded signals related by interference cancellation was first introduced in [8] and then extended to other space-time codes with a higher number of transmit antennas in [9]. In both works, interference cancellation was possible for perfectly synchronous signals. Later, the work of [7] extended the results to asynchronous signals in flat fading environments. In the current work, we further extend the results to frequency selective channels. What differentiates our work from the existing methods in the literature is the fact that we assume no time synchronization between multiple transmissions. We apply a simple linear interference cancellation technique for multiple-user detection as well as a more complex joint sphere-decoding detection scheme in order to evaluate the performance of our proposed technique via simulations. In addition, our method is suitable for multiple antenna nodes that utilize space-frequency block codes for transmission. Finally, our approach can be extended to OFDM coded transmissions by adding few extra signal processing steps.

The organization of the rest of the paper is as follows. In Section II, we explain our methodology for asynchronous transmission. Section III provides a discussion of multi-user detection over frequency selective channels. In Section IV, we discuss multi-user channel estimation using a pilot transmission technique. Simulation results are provided in Section V. Finally, Section VI concludes the paper.

II. DFT PROPERTIES AND PROPOSED SIGNAL FOLDING

A very efficient way to compensate against the effects of frequency selective channels is to apply frequency domain equalization. In such approach, the transmission bandwidth is split into different subcarriers by employing discrete Fourier transform (DFT) and hence allowing for per subcarrier processing. Since for large DFT sizes the channel can be consid-

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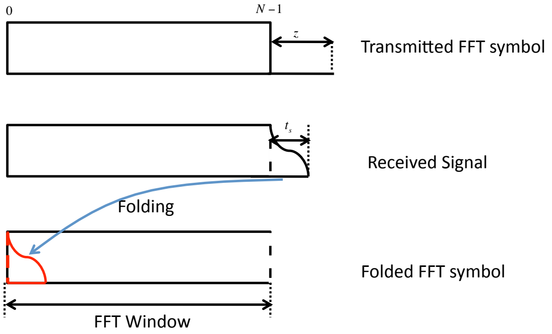


Fig. 1. The folding of a zero-padded FFT symbol.

ered flat over each subcarrier, MIMO approaches designed for flat fading channels can be employed per subcarrier. Methods such as OFDM and single carrier-OFDM constitute practical proposals of frequency domain equalization [4]. In this work, the concept of frequency domain processing is extended to allow for efficient interference cancellation in asynchronous space-frequency block coded systems. Similar to OFDM, our system transmits modulated data over different subcarriers and uses the inverse fast Fourier transform (IFFT) at the transmitter side to calculate the time domain equivalent of the signal to be transmitted. More specifically, a system with two users, each of which are equipped with two transmit and two receive antennas, is assumed. Each user employs space-frequency block coding which is the equivalent of Alamouti code in the frequency domain. In particular, the processing takes place in frames of N modulated symbols $\{S_1, S_2, ..., S_N\}$. Then, the space frequency coded symbols transmitted over N subcarriers of each antenna are expressed as

$$\begin{aligned} X_1 &= [S_1,\ -S_2^*,\ S_3,\ -S_4^*,\ ...,\ S_{N-1},\ -S_N^*] \\ X_2 &= [S_2,\ S_1^*,\ S_4,\ S_3^*,\ ...,\ S_N,\ S_{N-1}^*] \end{aligned} \quad (1)$$

Next, an N-point IFFT equal to the size of the frame is applied to each of the two transmit antennas before transmission. In order to perform efficient and simple frequency domain processing, circularity of the time domain signal is required. If we represent the N-point DFT with $\mathcal{F}$ and assume $\tilde{x}(n)$ is a circular time domain signal, we can express

$$\tilde{x}(n) * h(n) \overset{\mathcal{F}}{\longleftrightarrow} X(k)H(k) \quad (2)$$

where the operator * stands for linear convolution and

$$\tilde{x}(n) \overset{\mathcal{F}}{\longleftrightarrow} X(k)$$

$$h(n) \overset{\mathcal{F}}{\longleftrightarrow} H(k).$$

Assuming $h(n)$ is the transmission channel, $H(k)$ is the associated frequency response, and $X(k)$ represents the set of frequency-domain modulated symbols, it can be easily concluded that an independent per sub-carrier processing is permissible. In addition, MIMO approaches initially proposed for flat-fading channels can now be applied on a subcarrier basis. On the other hand, if the circular property does not hold, intercarrier-interference (ICI) appears and ICI cancellation methods are required as in the case of [10]. In order to retain circularity, typical frequency-domain processing approaches, e.g., OFDM, employ a cyclic prefix (CP) or zero-padding (ZP) added to the transmitted information [10]. However, in order for this approach to be efficient, the FFT window at the receiver side should be set directly after the CP. As shown in Fig. 1, the receiver folds the received signal over itself for ZP in order to reconstruct the circularity of the signal and the FFT window is set to the folded signal. Therefore, such approaches are not applicable to the case of several asynchronous users. Even if this property holds for one user, it will not hold for others. In order to retain circularity, a modified folding approach is proposed as illustrated in Fig. 2 with an N-point IFFT assumed at the transmitter. Without loss of generality, we assume that the signal of User A arrives first while the signal of User B arrives after δ sampling instants. Therefore, the effective length of the received signal is $N + \delta + t_s$, with t_s representing the channel delay spread. Our new folding strategy includes two steps. First, the signal is folded at point $N + \delta$ all the way back to point δ, i.e., the beginning of signal B. Then, the received signal will be folded starting from point N to point 0, i.e., the beginning of signal A. The second folding has two effects: (a) it restores the circularity for User A, and (b) it wraps around the signal of User B such that the FFT window of the two signals match in time. This folding process allows for restoring the required circularity with a very low complexity overhead. However, it also adds unwanted noise to our system, and therefore results in a decreased performance specially using larger values of δ. Fig. 2 illustrates the two-step folding process.

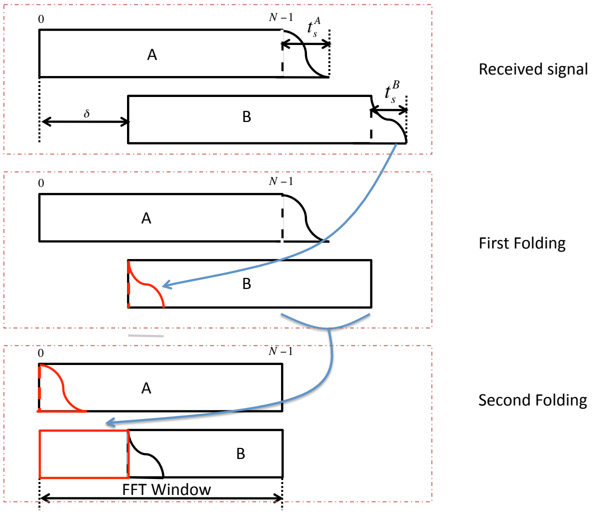


Fig. 2. The two-step folding process for asynchronous FFT symbols.

III. INTERFERENCE CANCELLATION AND JOINT USER DETECTION

After restoring circularity via folding, a folded signal can be assumed to be a circularly delayed version of the original signal. Since

$$h(n-\delta) \xrightarrow{\mathcal{F}} H[k]e^{-j\frac{2\pi k\delta}{N}} \tag{3}$$

the corresponding channel taps of the delayed user can be assumed to be the rotated version of the actual frequency response of the transmission channel. In order to perform space-frequency encoding and decoding, it is assumed that the channel frequency response between adjacent sub-carriers is approximately equal. This is a valid approximation for FFT sizes much larger than the channel spread. In addition, since the space-time decoding process takes place in pairs of sub-carriers, e.g., k, $k+1$, it can be assumed that the "effective" frequency response $A_{i,m}(j)$ of the channel between the i-th transmit antenna of User j and the m-th receive antenna are

$$A_{i,m}(1) = H^{(k)}_{i,m}(1) \approx H^{(k+1)}_{i,m}(1) \tag{4}$$

and

$$H_{i,m}(2) = A^{(k)}_{i,m}(2)\mathrm{e}^{-j\frac{2\pi}{N}\delta k} \tag{5}$$

with $H^{(k)}_{i,m}$ denoting the corresponding k-th subchannel frequency response. Then, if each user transmits the following Alamouti code:

$$\mathbf{C}(j) = \begin{pmatrix} S_1(j) & S_2(j) \\ -S_2^*(j) & S_1^*(j) \end{pmatrix} \tag{6}$$

over adjacent subcariers, we can use the approximations and the aforementioned DFT properties to formulate the folded received signal at the m-th antenna of the receiver as follows:

$$\begin{aligned} \begin{pmatrix} R_{1,m} \\ R_{2,m} \end{pmatrix} = & \begin{pmatrix} S_1(1) & S_2(1) \\ -S_2^*(1) & S_1^*(1) \end{pmatrix} \cdot \begin{pmatrix} A_{1,m}(1) \\ A_{2,m}(1) \end{pmatrix} \\ & + \begin{pmatrix} S_1(2) & S_2(2) \\ -S_2^*(2)e^{-j\frac{2\pi\delta}{N}} & S_1^*(2)e^{-j\frac{2\pi\delta}{N}} \end{pmatrix} \cdot \begin{pmatrix} A_{1,m}(2) \\ A_{2,m}(2) \end{pmatrix} \\ & + \begin{pmatrix} \eta_{1,m} \\ \eta_{2,m} \end{pmatrix} \end{aligned} \tag{7}$$

where $R_{k,m}$ is the received signal at Antenna m over Subcarrier k with $k = 1, 2$, $S_i(j)$ is the i-th transmitted symbol of User j as in Eq. (1), and $\eta_{k,m}$ are zero-mean Gaussian noise samples. Eq. (7) can be equivalently written as:

$$\begin{aligned} \mathbf{R}_m = \begin{pmatrix} R_{1,m} \\ R^*_{2,m} \end{pmatrix} = & \underbrace{\begin{pmatrix} A_{1,m}(1) & A_{2,m}(1) \\ A^*_{2,m}(1) & -A^*_{1,m}(1) \end{pmatrix}}_{\mathbf{A}_m(1)} \cdot \begin{pmatrix} S_1(1) \\ S_2(1) \end{pmatrix} \\ + & \underbrace{\begin{pmatrix} 1 & 0 \\ 0 & e^{j\frac{2\pi\delta}{N}} \end{pmatrix}}_{\mathbf{\Omega}} \underbrace{\begin{pmatrix} A_{1,m}(2) & A_{2,m}(2) \\ A^*_{2,m}(2) & -A^*_{1,m}(2) \end{pmatrix}}_{\mathbf{A}_m(2)} \cdot \begin{pmatrix} S_1(2) \\ S_2(2) \end{pmatrix} + \begin{pmatrix} \eta_{1,m} \\ \eta^*_{2,m} \end{pmatrix} \end{aligned} \tag{8}$$

The phase rotation matrix $\mathbf{\Omega}$ represents the linear phase shift across two adjacent subcarriers due to the delay δ of the second user which needs to be considered for efficient decoding. This representation of the received signal will be used in the next section to illustrate interference cancellation steps. The above equations show that the proposed folding scheme allows for the modeling of the received frequency domain observables in the case of space-frequency coding and frequency selective channels, in a way similar to the case of space-time coded signals and flat fading channels. Therefore, it allows for the use of already efficient multi-user methods proposed for flat fading channels, in the case of frequency selective channels with a very small complexity increase and performance degradation. If no folding is applied, the transmitted signals will interfere both in time and frequency domains preventing the use of methods similar to those in the time domain and requiring complex symbol interference cancellation methods. However and as discussed, the proposed folding method allows for using multi-user detection methods for flat fading channels (or frequency selective synchronous systems), with a small complexity overhead and performance loss. Hence, in the sequel we will examine how two different approaches, of different complexity and performance, can be extended for use with asynchronous frequency selective systems. We will also evaluate their performance through simulations. Specifically, we are going to examine the case of interference cancellation, which is a non-optimal, low-complexity approach, and the case of the significantly more complex approach of joint maximum-likelihood multi-user detection.

A. Interference Cancellation

To cancel interference, we use the received signal at different antennas, and exploit the fact that $\mathbf{A}_{i,m}(1)$ and $\mathbf{\Omega}\mathbf{A}_{i,m}(2)$ are unitary matrices. To cancel interference from User 2, $\mathbf{R}_i$'s are multiplied by the Hermitian transpose of the corresponding $\mathbf{\Omega}\mathbf{A}_{i,m}(2)$'s divided by the square of $\mathbf{A}_{i,m}(2)$'s determinant and the results are subtracted to reach the following signal:

$$\begin{aligned} & \frac{\mathbf{A}_2^H(2)\mathbf{R}_2}{|\mathbf{A}_2(2)|^2} - \frac{\mathbf{A}_1^H(2)\mathbf{R}_1}{|\mathbf{A}_1(2)|^2} \\ = & \underbrace{\left(\frac{\mathbf{A}_2^H(2)\mathbf{\Omega}^H\mathbf{A}_2(1)}{|\mathbf{A}_2(2)|^2} - \frac{\mathbf{A}_1^H(2)\mathbf{\Omega}^H\mathbf{A}_1(1)}{|\mathbf{A}_1(2)|^2} \right)}_{\mathbf{G}_1} \begin{pmatrix} S_1(1) \\ S_2(1) \end{pmatrix} + \begin{pmatrix} \eta'_{1,m} \\ \eta'_{2,m} \end{pmatrix} \end{aligned} \tag{9}$$

Then, the signal from User 1 can be decoded interference free. Note that matrix $\mathbf{G}_1$ is a unitary matrix and a simple symbol-by-symbol detection is possible for each user's symbols. To detect the symbols, we pre-multiply Eq. (9) by $\mathbf{G}_1^H$ and make hard decisions about $S_1(1)$ and $S_2(1)$, separately. Therefore, interference cancellation and symbol-by-symbol decoding for the asynchronous case is possible. Similar steps can be taken to cancel the interference from User 1 and decode the symbols of User 2 one by one. If transmitters and the receiver have two antennas each, the method provides a diversity of 2 for each user. Compared to the synchronous case, the folded signal has an additional folded noise on folded samples and the phase rotation $\mathbf{\Omega}$ for the folded user, but interference cancellation and interference free detection steps are similar. Note that the folding method can be easily extended to a case in which more than $N > 2$ packets are over-lapping and thereby unify the FFT window setting of all users. Then, the receiver with at least N antennas can cancel interference from all $N-1$ other undesired users following the interference cancellation steps described above.

B. Joint User Detection

Equivalent to Eq. (8), the received signal can be expressed as

$$\begin{pmatrix} R_{1,1} \\ R_{2,1}^* \\ R_{1,2} \\ R_{2,2}^* \end{pmatrix} = \tilde{\mathbf{A}} \begin{pmatrix} S_1(1) \\ S_2(1) \\ S_1(2) \\ S_2(2) \end{pmatrix} + \begin{pmatrix} \eta_{1,1} \\ \eta_{2,1}^* \\ \eta_{1,2} \\ \eta_{2,2}^* \end{pmatrix} \tag{10}$$

with

$$\tilde{\mathbf{A}} = \begin{pmatrix} \mathbf{A}_1(1) & \mathbf{\Omega}\mathbf{A}_1(2) \\ \mathbf{A}_2(1) & \mathbf{\Omega}\mathbf{A}_2(2) \end{pmatrix}.$$

From the equation above, the symbols of both users can be jointly decoded at the same time. Under the assumption that the noise samples are independent with the same variance, the maximum-likelihood (ML) detection of the transmitted symbols would result in

$$\begin{pmatrix} \hat{S}_1(1) \\ \hat{S}_2(1) \\ \hat{S}_1(2) \\ \hat{S}_2(2) \end{pmatrix} = \underset{S_1(1),S_2(1),S_1(2),S_2(2)}{\arg\min} \left\| \begin{pmatrix} R_{1,1} \\ R_{2,1}^* \\ R_{1,2} \\ R_{2,2}^* \end{pmatrix} - \tilde{\mathbf{A}} \begin{pmatrix} S_1(1) \\ S_2(1) \\ S_1(2) \\ S_2(2) \end{pmatrix} \right\|^2 \tag{11}$$

Therefore, optimal detection would require an exhaustive search over all possible symbols, which leads to prohibitive processing complexity, especially for high order constellations. This problem is typically tackled by QR decomposition of the channel matrix $\tilde{\mathbf{A}}$. Then, the problem is transformed into an equivalent tree-search which can be efficiently solved by means of sphere decoding. In detail, the channel matrix $\tilde{\mathbf{A}}$ can be QR decomposed into $\tilde{\mathbf{A}} = \mathbf{Q_A}\mathbf{R_A}$, with $\mathbf{Q_A}$ representing a unitary 4×4 and $\mathbf{R_A}$ representing a 4×4 upper triangular matrix. Then, the corresponding problem is transformed to finding the symbol vector minimizing the metric

$$\left\| \mathbf{Q}_\mathbf{A}^H \begin{pmatrix} R_{1,1} \\ R_{2,1}^* \\ R_{1,2} \\ R_{2,2}^* \end{pmatrix} - \mathbf{R_A} \begin{pmatrix} S_1(1) \\ S_2(1) \\ S_1(2) \\ S_2(2) \end{pmatrix} \right\|^2$$

Since $\mathbf{R_A}$ is triangular, the above optimization can be translated to a tree search problem, with several existing solutions in the literature, for example [11]–[15] and references therein. Note that assuming equal adjacent subcarriers and uncorrelated noise results in a diversity of 4. However and as shown in Section VI, the adjacent subcarriers are not exactly equal resulting in a small diversity loss in practice.

IV. CHANNEL ESTIMATION

One additional challenge in multi-user detection of asynchronous users is their simultaneous channel estimation. In this section, we show a hand-waving solution to channel estimation problem. without going through all of the details, we show how the proposed approach could be efficiently applied. To enable channel estimation, each user transmits a pilot prefix before data packet transmission and a suffix after it. Each pilot symbol is formed by transmitting a known training sequence over selected pilot subcarriers.

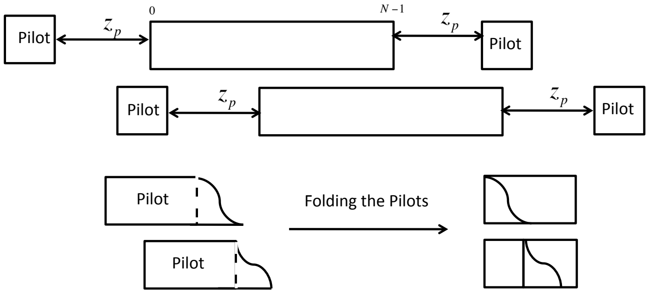


Fig. 3. Two different options for suffix transmission.

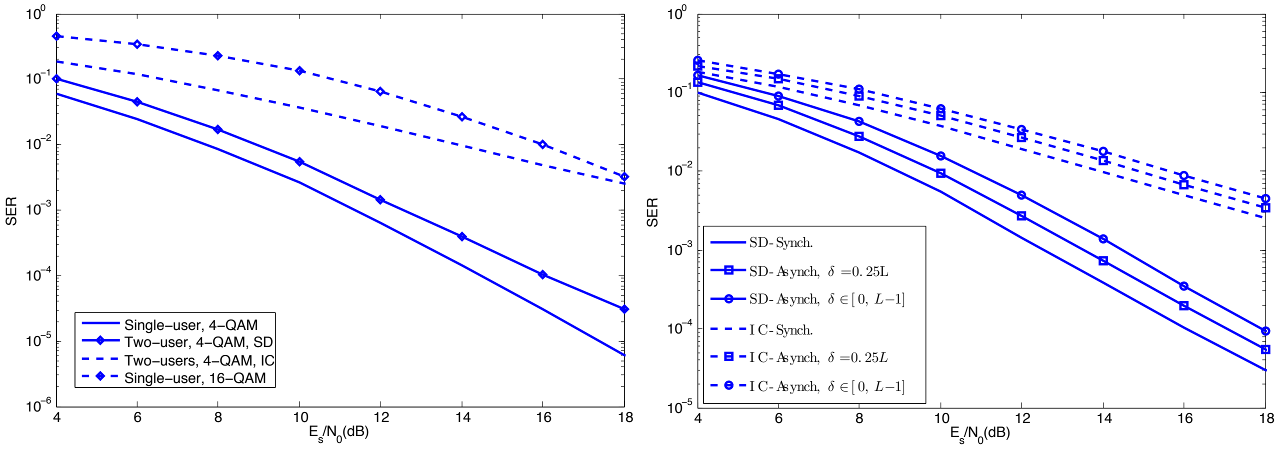
As illustrated in Fig. 3, each transmitter sends the following sequence: a pilot symbol of length p, z_p zero symbols, the FFT data symbol, z_p zeros, and a second pilot symbol. In case of having a large delay between the two signals, $\delta > p + \max\ t_s^i$, each user has an interference free pilot symbol to be used for channel estimation. For smaller delays, both prefix and suffix pilot symbols will interfere with the other users pilot symbols. For small delays, the channel estimator can use the same folding process as the one in Section II in order to match the FFT window of the two pilots. In this case, the channel estimation algorithm estimates the two users' channel coefficients simultaneously. Note that folding is performed on both prefix and suffix pilot symbols providing a redundant pilot which can be used to average out the noise effect. One last point is that depending on the folding process, there are two choices for the size of z_p. First, z_p has to be at least twice as long as the delay spread of the channel plus p if the estimator performs the previously explained pilot folding. Second, z_p can be as short as the delay spread of the channel plus p if the suffix and prefix are used jointly for folding when $p < \delta < p + \max\ t_s^i$.

As Fig. 3 illustrates, one of the pilot symbols of each user overlaps with the useful data of the other user. In this case, interference from the pilot symbol cannot be canceled by the method of Section III. However, one can easily regenerate a copy of the interfering pilot symbol and subtract it from the received signal before proceeding to applying the folding process for the FFT data symbol, given that the pilot symbol is known at the receiver and that the channel can be estimated with methods explained in this section.

V. NUMERICAL RESULTS

For the purpose of numerical validation and performance evaluation of the proposed scheme, frames of FFT size of $N = 512$ are used. The transmission channel is a quasi-static Rayleigh fading channel varying independently on a per frame basis. The multipath channel is assumed to have a delay spread of $t_s = 16$ taps. Further, the fading channel taps are independent and identically distributed (i.i.d.) complex Gaussian random variables.

Fig. 4(a) compares the performance of multi-user detection in synchronous networks against that of the single-user transmission. In order to implement the ML joint multi-user detec-



(a) (b)

Fig. 4. Illustrations of the performance of multi-user detection schemes in (a) synchronous, and (b) asynchronous networks compared to a single-user transmission scheme.

tion, a sphere decoding (SD) algorithm is utilized. The slope of the symbol error rate (SER) curves from the joint multi-user detection is lower than that of the corresponding single-user scheme. As discussed earlier, because of the frequency-selectivity of the channel, adjacent subcarriers have slightly different frequency responses. This imperfection affects the achievable diversity by SFBC compared to the ideal case and lowers the diversity of the 2×2 system to approximately 3.5 in Fig. 4(a). For joint multiuser detection, the channel imperfection has a more sever effect as there are twice as many channel coefficients to be considered as those of the single-user case. The SER curve of the linear interference cancellation method in Eq. (9) has even a lower slope than that of SD trading off the simple receiver structure with a lower diversity gain. The last curve represents the performance of a single-user scheme where its rate is equal to the sum rate of the two-user system, i.e., the transmission rate is doubled. Note that doubling the rate doubles the complexity of the ML receiver. In the studied SNR range, linear interference cancellation of the single-rate double-user case outperforms the double-rate single-user case. Results in Fig. 4(a) highlight the fact that using a multiple-user detection scheme will in fact improve the performance of the system.

Fig. 4(b) illustrates the performance of asynchronous multi-user detection using the folding method of this paper. After folding the received signal, the receiver might use the ML decoder or the linear interference cancellation in Eq. (9). In either case, the folding process folds the receiver noise as well as the desired signal. Hence, a coding gain loss is expected if the detector uses the folded signal instead of the synchronous signal. In Fig. 4(b), the cases of fixed delay and random delay between two packets are illustrated. For a packet length of L and a random delay in the range of $[0, L]$ between the two packets, there is a $2\ dB$ performance loss. However, fixing the delay between the two packets to 25% of the packet length lowers the performance loss down to $1\ dB$. The performance loss is independent of the receiver choice of the decoder. Note that folding the noise signal generates variable variance noise samples in the time domain. In frequency domain, though, folding correlates the noise samples. However and as observed in Fig. 4(b), the slope of SER curves are the same for synchronous and asynchronous folded scenarios implying that there is no diversity loss due to the folding of the packets.

To summarize, the folding idea proposed in this paper introduces an effective way of building a simple structured receiver capable of detecting multiple overlapping packets and resulting in an acceptable performance.

VI. CONCLUSIONS

This paper proposed a new framework for multi-user detection of asynchronous users employing space-frequency codes and operating over MIMO frequency selective environments. The proposed framework extended the previously proposed interference mitigation and joint multi-user detection for synchronous systems with a low complexity overhead and a small performance loss compared to the synchronous case. Our simulation results validated our proposed technique. We note that our proposed approach can also be extended to OFDM systems.

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