Cooperative Scheme Using STNC for Uplink SC-FDMA and Downlink OFDMA System

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Abstract—Orthogonal frequency-division multiplexing (OFDM) has recently developed as one of the most popular schemes to overcome multipath fading. Single carrier frequency division multiple access (SC-FDMA) has also been adopted as an alternative of OFDMA for uplink transmission in UTRA LTE. To improve the performance of OFDMA and SC-FDMA, cooperative communication can be used. However, traditional cooperative protocol for multi-carrier system suffers with the issue of imperfect synchronization. TDMA scheme in which each node in the network transmits symbols in its dedicated time slot can solve the asynchronous problem but gives rise to large time delay. In this paper, a novel cooperative scheme by using space-time network coding (STNC) for uplink SC-FDMA and downlink OFDMA system is proposed. For a SC-FDMA/OFDMA system consists of N users and R relay nodes, a full diversity order of R+1 can be achieved while keeping the delay low and the issue of asynchronization is eliminated. Compare with the TDMA scheme where N(R+1) time slots is required to complete the transmission of a symbol frame, only N+R time slots is needed in our proposed scheme by using STNC at relay nodes.

Keywords—SC-FDMA; OFDMA; Space-time network coding; Cooperative communications; Decode and forward protocol; Amplified and forward protocol.

I. INTRODUCTION

In wireless networks, the performance of communication systems degrades severely due to signal fading arising from multipath propagation. Diversity techniques such as time diversity, frequency diversity and spatial diversity can be utilize to combat fading and co-channel interference by using two or more communication channels with different characteristics. Among these techniques, spatial diversity [1][2] which is realized by cooperative communication has attracted a lot of research interest due to its possible use in cellular, sensor network and multiple-input and multiple-output (MIMO) system.

A conventional single hop system uses direct transmission where a receiver decodes the information only based on the direct signal, while in cooperative communication, some nodes act as relays to retransmit overheard information. Hence, it can be seen that cooperative diversity is an antenna diversity that uses distributed antennas belonging to source and relays in a wireless network.

In broadband communications, orthogonal frequency-division multiplexing (OFDM) has developed into one of the most popular schemes to overcome multipath fading [3] and inter-symbol interferences (ISI), while providing high spectral efficiency. The OFDM based multiple access technology OFDMA has been widely accepted by several 4G and pre-4G cellular networks and mobile broadband standards, such as IEEE 802.16e and 3GPP long term evolution(LTE).

In order to mitigate the problem of peak-to-average power ratio (PAPR) encountered in uplink OFDMA, single carrier frequency division multiple access (SC-FDMA) has been adopted for uplink transmission in UTRA LTE [4]-[7]. SC-FDMA can be seen as a linearly precoded OFDMA scheme which has an additional DFT operation preceding the conventional OFDMA. SC-FDMA has drawn great attention as an alternative to OFDMA in the uplink communication because of its lower PAPR, which can enhance the transmit power efficiency of mobile terminal.

To improve the performance of OFDMA and SC-FDMA system, traditional cooperative scheme can be applied. However, much of research has only concentrated on simultaneous transmission from two or more node with an assumption of perfect frequency and timing synchronization [8][9]. Such an assumption is difficult to be met in a practical scenario, especially in mobile communication where nodes move in different speed and different directions. For timing synchronization, it is difficult to make signals transmitted from different nodes arrive simultaneous at a destination node due to path delay difference between different users. For frequency synchronization, carrier frequency offset (CFO) introduced by Doppler effects and poor oscillator alignment are also encountered in cooperative OFDMA and SC-FDMA systems. Large CFO and timing offset (TO) can cause severely multiuser interference. Sensitivity of uplink OFDMA performance to CFO and TO is given in [10][11].

One of the methods to combat imperfect synchronization in SC-FDMA or OFDMA system is to prevent two or more users from transmitting messages simultaneously, for example using
time-division multiple access (TDMA) technology. Such a scheme is widely applied in many scenarios in which each node transmits in turn and a pilot can easily overcome the CFO and TO. However, \(N(R+1)\) time slots are required to complete the transmission in a system with \(N\) source nodes and \(R\) relays by using a TDMA strategy. This will cause great delay when \(N\) and \(R\) is large.

To solve problems of asynchronization while maintaining the spatial diversity and keeping the delay low, we will propose a novel scheme for cooperative OFDM and SC-FDMA by using space-time network coding (STNC), for a SC-FDMA/OFDMA system consist of \(N\) users,\( R\) relays and a base node. In the rest of this work, we first present the system model in Section II. Multiuser detection and the simulation of BER performance are presented in Section III and Section IV. At last, some conclusions will be given in Section V.

II. SYSTEM MODEL

In this section, we first introduce the concept of space-time network coding (STNC) presented in [12][13] that will be employed throughout the paper. Secondly, system models of downlink OFDMA and uplink SC-FDMA using space-time network coding in relaying scheme are presented. Both DF and AF protocol is considered. Difference between the model employed in this paper and the one employed in [12][13] lies in that the multicarrier cooperative system is considered and a different signal combining technology is utilized.

A. Concept of Space-Time Network Coding [13]

Consider a cellular based mobile communication system with \(N\) users, \(R\) relays and a base node. Each user, denoted as \(U_i\) for \(i = 1,2,...,N\), wants to transmit statistically independent data to a base node. \(R\) relays, denoted as \(R_1,R_2,...,R_R\), help to forward the users information. Let \(x_1,x_2,...,x_N\) denote the users date symbols and \(U_0\) denotes the base node.

In the source transmission phase, users broadcast information in their own dedicated time slots. In the end of the \(N\)th time slot, each relay possesses a set of overheard symbols, denoted as \(x = [x_1,x_2,...,x_N]^T\), under the assumption that relays can decode all the users’ symbols correctly. In the relay transmission phase, different from the traditional cooperative communications which two or more relays can transmit information simultaneously, relay nodes encode the overheard symbols as a single signal, denoted as \(f_r(x)\) where \(r = 1,2,...,R\), then transmit the combined signal to the base node in its dedicated time slot. The set of encoding function \(\{f_r, r = 1,2,...,N\}\) form a STNC that keep the delay low while maintaining the full cooperative diversity in cooperative communication.

The signal combination from different user nodes gives rise to the concept of network coding and transmission at dedicated time slot gives rise to the concept of space-time. Fig.1 depicts the framework of STNC. Relays combine the symbols from different users with a set of waveform, denoted as \(s_n(t)\), i.e.,

\[
f(x) = \sum_n x_n s_n(t),
\]

where \(s_n(t)\) presents the dedicated carrier, spreading code and time duration of symbol \(x_n\) in FDMA, CDMA and TDMA scheme respectively. Note that the STNC scheme will not provide more bandwidth efficiency than traditional FDMA, CDMA and TDMA in cooperative communication due to its method of information combining employed in the relay node.

B. Channel Model

It is supposed that the transmitted signals propagate through a multipath channel which is modeled in the time domain by \(L\) delayed impulses with additive white Gaussian noise.

That is \(h_{uv_l}(t,\tau) = \sum_{i=0}^{L-1} h_{uv_i}(l) \delta(t - \tau_{uv_i}(l))\), \(\tau_i\) is the delay of the \(i^{th}\) path, and \(h_{uv_i}(l)\) is modeled as a zero mean circularly symmetric complex Gaussian random variable with zero mean and variance \(\sigma_{u,v}^2(l)\), and \(\sum_{i=0}^{L-1} \sigma_{u,v}^2(l) = 1\). Thus the channel frequency response can be expressed as

\[
H_{uv}(k) = \sum_{l=0}^{L-1} h_{uv_i}(l) \exp(-j2\pi \tau_{uv_i}(l)k/M).
\]

Let \(\alpha\) and \(d_{uv}\) denote the pass loss factor and the distance between node \(u\) and \(v\) respectively, thus the received signal-to-noise ratio (SNR) for the \(k_{th}\) subcarrier can be given by

\[
\gamma(k) = \frac{d_{uv}^{-\alpha} |H_{uv}(k)|^2}{N_0},
\]
with assumption that each information symbol has unit energy. In the rest of this paper, we define a $M \times M$ order diagonal matrix $H_{u,v}$ as the channel frequency response matrix between nodes $u$ and $v$, $H_{u,v} = \text{diag} \left( H_{u,1}, H_{u,2}, \ldots, H_{u,M} \right)$, in which $M$ is the FFT size of an OFDMA/SC-FDMA system.

### C. Uplink Cooperative SC-FDMA Transmission with Space-Time Network Coding

We consider a system with $N$ users and $M$ subcarriers. $K$ subcarriers, $K = M/N$, are allocated to each user and each subcarrier can only be utilized by one user. Fig. 2 illustrates the transmission in source and relay transmission phase of the proposed uplink SC-FDMA scheme, where $N$ users $U_1, U_2, \ldots, U_N$ transmit their symbols to the base node $U_0$. As shown in Fig. 2, in order to eliminate the asynchronous issue, the system need $N + R$ time slots to complete all transmissions instead of $N(R+1)$ time slots in traditional TDMA cooperative communication while keep a single transmission in each time slot. Different from STNC scheme in [10], we let

$$x^i = [x^i_1, x^i_2, \ldots, x^i_M]^T$$

(4)
denote the $i$th user’s complex data symbol frame of size $K$, where each information symbol $x^i_k$ is drawn from a $M$PSK constellation. The transmit power $P^i_d$ allocated to $x^i$ is distributed among source node and relay nodes, that is $P^i_d = P^i + \sum_{r=1}^{R} P^r_i$, in which $P^i$ and $P^r_i$ is the power allocated to $U_i$ and $R_r$, respectively. Denoting the $Q$-point normalized DFT and IDFT matrix by $\tilde{F}_u$ and $\tilde{F}_v$, respectively, and the subcarrier mapping matrix of the $i$th user by $M^i$ where

$$M^i_{j,k} = \begin{cases} 1, & \text{if } j\text{th subcarrier is allocated to the} \\ 0, & \text{otherwise} \\ \end{cases}$$

(5)
is a $M \times K$ order matrix.

In the source transmission phase, $i$th user, for $i = 1, 2, \ldots, N$, transmits its SC-FDMA symbol frame to the base node $U_0$ and relays in its dedicated time slot $T_i$. The output of $M$-point IFFT of $i$th user is

$$u_i = \tilde{F}_u M F K x^i,$$

(6)
and the received signals after dropping the cyclic prefix at $U_0$ and $R_r$ are

$$y_{i,0} = \sqrt{P^i_d} d_{i,0} x^i \ast h_{i,0} + w_{i,0},$$

(7)
and

$$y_{i,r} = \sqrt{P^i_d} d_{i,r} x^i \ast h_{i,r} + w_{i,r},$$

(8)
where $\ast$ indicates the $M$-point circular convolution and $w_{i,x} = [w_{i,x}(1), w_{i,x}(2), \ldots, w_{i,x}(K)]^T$ is the complex noise vector, $w_{i,x} \sim N(0, N[I_M])$. Substitute (6) into equation (7) (8) and apply $M$-point FFT , we have

$$Y_{i,0} = \sqrt{P^i_d} d_{i,0} H_{i,0} M F K x^i + W_{i,0},$$

(9)
and

$$Y_{i,r} = \sqrt{P^i_d} d_{i,r} H_{i,r} M F K x^i + W_{i,r},$$

(10)
where $Y_{i,x} = [Y_{i,x}(1), Y_{i,x}(2), \ldots, Y_{i,x}(K)]^T$ is the frequency domain soft information vector of $i$th user and $w_{i,x} = F_M w_{i,x}$ is the complex noise vector in frequency domain. In the end of this phase, each relay node possesses a set of $N$ frequency symbol frames $X_1, X_2, \ldots, X_N$ by using a MMSE equalizer, in which $X = M F K x^i$ , for $r = 1, 2, \ldots, R$, employs a linear network coding in frequency domain to the information vectors and forms a single signal, then transmits it to the base node in its dedicated time slot $T_r$ after a $M$-point IFFT operation. The output of $M$-point FFT at base node in the end of the relay transmission phase is

$$Y_{r,0} = H_{r,0} \sum_{i=1}^{N} \sqrt{P^i_d} d_{r,0} M F K x^i + W_{r,0},$$

(11)
where
\[ \hat{P}_r = \begin{cases} P_r', & \text{if } R_r \text{ decodes } x_i \text{ successfully} \\ 0, & \text{otherwise} \end{cases} \]

in DF protocol and

\[ \hat{P}_r' = \frac{P_r' P_i'}{P_i' + N_0} \quad (12) \]

for the case of AF protocol. \( W_{r,0} \sim N(0, \lambda_r N_0 I_M) \) is the complex noise vector, where

\[ \lambda_r = \begin{cases} 1, & \text{for DF protocol} \\ 1 + \frac{1}{P_i' + N_0}, & \text{for AF protocol} \end{cases} \quad (13) \]

is a factor presenting the impact of noise amplification at \( R_r \) on \( U_0 \)'s received SNR.

### D. Downlink Cooperative OFDMA Transmission with Space-Time Network Coding

Fig. 3 illustrates source and relay transmission phases of the proposed downlink OFDMA scheme. We also suppose a system with \( N \) users and \( M \) subcarriers, in which \( K \) subcarriers, \( K = M / N \), are allocated to each user and each subcarrier can only be utilized by one user. Base node \( U_0 \) transmits information symbol frames, denoted as \( X^1, X^2, ..., X^N \), to \( N \) users, in which \( X = [x_1^T, x_2^T, ..., x_N^T] \).

By using space-time network coding in relay nodes, only \( NR + \) time slots is needed to complete the transmissions and the issue of imperfect synchronization is controlled. It can be seen from the figure that the downlink cooperative OFDMA scheme with STNC has almost the same transmission manner with the uplink cooperative SC-FDMA model, thus we only give the final expression of the received signals in source and relay transmission phases.

The output of \( M \)-point FFT of the received signals at user \( U_i \) and relay \( R_r \) after dropping the cyclic prefix are

\[ Y_{o,j} = \sqrt{P_r} d_{o,j} H_{o,j} M_j X^i + W_{o,j} \quad (14) \]

and

\[ Y_{o,r} = \sqrt{P_r} d_{o,r} H_{o,r} M_r X^i + W_{o,r} \quad (15) \]

respectively, in which \( W_{o,j} \sim N(0, N_0 I_M) \) is the complex noise vector. In relay transmission phase, the frequency domain expression of the received signal at \( U_r \) is

\[ Y_{r,j} = H_{r,j} \sum_{i=1}^{N} \sqrt{P_{r,j}'} M_j X_j^i + W_{r,j} \quad (16) \]

in which \( W_{r,j} \sim N(0, \lambda_r N_0 I_M) \) is the complex noise vector. The \( \hat{P}_r' \) and \( \lambda_r \) have the same expression with equation (11) and (12) respectively.

### III. Multiuser Detection

It is supposed that relays and the destination node have a full knowledge of channel state information (CSI) which can be obtained by using a pilot in the transmitted signals. In the case of DF protocol, we also suppose that the destination node \( (U_0 \text{ for uplink scheme and } U_n \text{ for downlink scheme}) \) knows the detection states at the relay nodes.

It can seen in section II that the uplink SC-FDMA scheme and downlink OFDMA scheme share a similar transmission model, except for the different destination node and a precoding operation for SC-FDMA. Note that the \( M \) – point FFT output of received signals at destination node for the downlink OFDMA scheme can be obtained from (9) and (11) by making \( F_k = \tilde{F}_k = I_k \). Therefore in the rest of this section, we only present the multiuser detection for uplink space-time network coded cooperative SC-FDMA scheme, and the detection of downlink OFDMA scheme is straightforward.

A decorrelator and a maximal ratio combining unit is involved in the proposed multiuser detector. In the end of relay transmission phase, the base node \( U_0 \) in uplink SC-FDMA scheme obtains \( R + 1 \) signals that contain symbol frame \( x^i \). From these signals, \( U_0 \) gets \( R + 1 \) soft symbol frames associated with \( x^i \) in frequency domain by using a decorrelator and then a maximal ratio combining unit is employed to detect the symbol frame \( x^i \). Note that in practical SC-FDMA system, the decorrelator can be replaced by a FFT unit and a demapping matrix. Defining \( \bar{M}_i = (M_i)^T \) as the demapping matrix of \( i \)-th user, in which \( T \) denotes the transpose operation. The first soft symbol frame comes from direct link in the source transmission phase by using a \( M \) – point FFT and a demapping operation, that is
\[ Y_{DL} = \tilde{M}_i F_{M} Y_{0,i} \]  

by using equation (7) and (9) we have

\[ Y_{DL} = \sqrt{P_i} d_{i,0}^{\alpha} \tilde{M}_i F_M \tilde{F}_M \bar{H}_{i,0} M_i F_{K} x_i + \tilde{M}_i F_M w_{i,0}. \]  

The remaining \( R \) soft symbol frames are extracted from the relays’ signal in relay transmission phase by employing the same operations. The received signal from \( R_r \), for \( r = 1, 2, \ldots, R \), is applied by a M point FFT and multiplied the demapping matrix \( \tilde{M}_i \) of \( i \)th user, i.e.,

\[ Y'_{r,DL} = \tilde{M}_j F_M \tilde{F}_M \bar{H}_{r,0} \sum_{j=1}^{N} \sqrt{P_j} d_{r,0}^{\alpha} M_j F_{K} x_j + \tilde{M}_i F_M w_{r,0}. \]  

Since \( F_M \tilde{F}_M = I_M \) and

\[ \tilde{M}_i M_j = \begin{cases} I_M, & \text{for } i=j \\ 0_M, & \text{otherwise} \end{cases} \]

let \( \tilde{M}_i H_{x,0} M_j = \tilde{H}_{i,0} \), then we rewrite (18) (19) as

\[ Y_{i,DL} = \sqrt{P_i} d_{i,0}^{\alpha} \tilde{H}_{i,0} F_{K} x_i + W_{i,DL} \]  

and

\[ Y'_{r,DL} = \sqrt{P_j} d_{r,0}^{\alpha} \tilde{H}_{r,0} F_{K} x_j + W'_{r,DL} \]  

in which \( W_{i,DL} \sim N(0, N_0 I_K) \) and \( W'_{r,DL} \sim N(0, \lambda_i N_0 I_M) \), are the noise vectors in frequency domain. Note that \( \tilde{H}_{i,0} \) is also a diagonal matrix of \( K \times K \) size. Since there are \( R \) relays, \( U_0 \) acquires \( R \) soft symbol frames of \( x' \) in the above method. Let \( Y_i = [Y_{i,DL}, Y_{i,RL}^1, Y_{i,RL}^2, \ldots, Y_{i,RL}^R] \), and

\[ B_i = \begin{bmatrix} \sqrt{P_i} d_{i,0}^{\alpha} \tilde{H}_{i,0} \bar{H}_{i,0} & \sqrt{P_i} d_{i,0}^{\alpha} \tilde{H}_{i,0} \bar{H}_{i,0} & \sqrt{P_i} d_{i,0}^{\alpha} \tilde{H}_{i,0} \bar{H}_{i,0} & \ldots & \sqrt{P_i} d_{i,0}^{\alpha} \tilde{H}_{i,0} \bar{H}_{i,0} \end{bmatrix} \]

as the weight matrix of maximal ratio combining. Thus the symbol frame can be estimated by

\[ \hat{x}_i = \tilde{F}_K B_i^* Y_i = b_i x_i + w_i, \]  

in which \( b_i = \frac{P_i d_{i,0}^{\alpha} \tilde{H}_{i,0}^2}{N_0} + \sum_{r=1}^{R} \frac{P_i d_{r,0}^{\alpha} \tilde{H}_{r,0}^2}{\lambda_i N_0} \) is a diagonal matrix and \( w_i \sim N(0, b_i) \). We use \( \tilde{H}^2 \) and \((\cdot)^*\) to denote the \( \tilde{H} \tilde{H}^* \) and conjugate operation respectively.

**IV. SIMULATION RESULTS**

In this section, computer simulation results of the proposed uplink cooperative SC-FDMA scheme and downlink cooperative OFDMA scheme with STNC are presented. For the simulation setup, we consider a cellular based system with \( N = 8 \) users, \( M = 256 \) subcarriers and various numbers of relay nodes in which \( BPSK \) modulation is used. Channels between \( S \to R, S \to D \) and \( R \to D \) are modeled as four–tap frequency-selective fading and are assumed to be constant over a SC-FDMA or OFDM symbol frame. Relays is arranged with the equal distance to base node and user nodes, thus we can let pass loss component \( d_{i,0}^{\alpha} = d_{0i}^{\alpha} = 1 \) and \( d_{r,i}^{\alpha} = d_{r,i}^{\alpha} = d_{i,0}^{\alpha} = 6 \) for all \( i \) and \( r \). Transmit power allocated to \( i \)th user is the same for all \( i \) and equal power. The simulation results of direct transmission scheme,
in which source nodes transmit directly to the base node reference. To ensure a fair comparison, the power of each user $P_{i,d}$ is entirely allocated to the source node in the direct transmission scheme.

Fig. 4 presents BER performance of uplink cooperative SC-FDMA scheme using STNC with the parameter given above for both DF and AF protocol. It can be seen from the figure that the proposed scheme improve the BER performance of SC-FDMA system. And the SNR gain becomes large due to the increase of relay number given the same BER. Fig. 5 depicts the BER performance of the downlink cooperative OFDMA scheme using STNC. Similar conclusion can be drawn as the case of SC-FDMA scheme.

V. CONCLUSION

In this paper, schemes of cooperative communication using space-time network coding for uplink SC-FDMA and downlink OFDMA systems are proposed. For a SC-FDMA/OFDMA system consists of $N$ users, $R$ relays and a base node, such a scheme can get a full diversity of order $R+1$ and the issue of imperfect synchronization in traditional cooperative communications is eliminated. Only $N+R$ time slots is needed to complete the transmission of a SC-FDMA/OFDMA symbol frame, a sharp reduction comparing with the traditional TDMA scheme, in which $N(R+1)$ are required. Furthermore, simulation results have revealed that the proposed scheme acquires a SNR gain comparing with the direct transmission scheme for a given BER.

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