Location-Aware Cooperative Communications utilizing Linear Network Coding

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***Abstract*— Cooperative communication can be used to reduce the transmit power of distant mobile units, compared to conventional direct transmission, given the same quality-of-service. However, imposing the constraint of having orthogonal transmission for the source and relays leads to large delay in TDMA systems. For a network of N mobile units, the transmission delay would be $N(N+1)/2$. In this work, we propose a location-aware cooperation-based scheme that aims to reduce transmit power of distant mobile units while maintaining a low transmission delay. The scheme utilizes a linear network coding protocol, where each mobile unit applies linear network coding to a set of transmit symbols that it has received previously. At the base station, multiuser detection is used to decouple the transmit symbols. Both decode-and-forward and amplify-and-forward cooperative protocols are considered. We show that our proposed scheme achieves a comparable bit-error-rate performance with the conventional cooperation-based TDMA scheme while requiring a delay of $(2N-1)$ time slots, a substantial reduction in the transmission delay.**

I. INTRODUCTION

In the nature of wireless communications, information from distant mobile units (MUs) to a common base station (BS) requires more transmit power in direct transmission. The additional transmit power is to compensate the large scale fading in order to provide a comparable quality of service (QoS) to that of the close ones. Diversity techniques such as time diversity, frequency diversity, and spatial diversity can result in reduction of transmit power. Among these techniques, spatial diversity achieved by cooperative communication has become recently attractive.

In cooperative communication, MUs in a network acting as relays can process the transmissions overheard from other units. The distributed antennas among the relays are used to provide spatial diversity without the need to use multiple antennas at the source. Various cooperative diversity protocols have been proposed and analyzed in [1]-[6]. Decode-and-forward (DAF) and amplify-and-forward (AAF) protocols for cooperative communications are explained in [1]. In DAF protocol, each relay decodes the overheard information from the source, re-encodes it, and then forwards it to the destination. In AAF protocol, each relay simply amplifies the overheard signal and forwards it to the destination. The symbol error rate (SER) for single- and multi-relay DAF protocol was analyzed in [2], [3]. In [4], [5], various relay selection schemes have been proposed that achieve high bandwidth efficiency and full diversity order. Finally, distributed space time codes for DAF and AAF protocols have been proposed and analyzed in [6].

Cooperative communication with its ability to achieve spatial diversity can be used to reduce the transmit power of distant MUs to a common BS in location-aware networks, where locations of nodes are taken into consideration to improve network performance. However, the constraint that source and relay transmissions are over orthogonal channels such as time division multiple access (TDMA) leads to a large transmission delay. For a network of N MUs, the transmission delay would be $N(N+1)/2$. In this work, we propose a location-aware cooperation-based scheme that aims to reduce transmit power of distant MUs while maintaining a low transmission delay. The scheme uses network coding, where each mobile unit applies linear network coding to a set of transmit symbols that it has received previously to form a unique signal and transmits it to the BS. At the base station, multiuser detection is used to decouple the transmit symbols. Both DAF and AAF protocols in cooperative communications are considered in our proposed scheme. For the validation purpose, the performance analysis is based on BPSK modulation; nevertheless, the extension to general M-PSK and M-QAM can follow directly. We show that our proposed scheme achieves a comparable bit-error-rate (BER) performance with the conventional cooperation-based TDMA scheme while it requires a delay of $(2N-1)$ time slots, a substantial reduction in transmission delays. Note that only simple detection is required at MUs in our proposed scheme.

This paper is outlined as follows. After this introduction section, our proposed location-aware cooperation-based scheme for DAF and AAF protocols are introduced in Section II. Multiuser detection used in our proposed scheme is presented in Section III for both DAF and AAF protocols. The performance analysis is presented in Section IV to provide a close-form BER expression for DAF protocol and a conditional BER expression for AAF protocol. These expressions then are used in Section V to obtain analytical and numerical results that validate our proposed scheme. Lastly, we draw some conclusions in Section VI.

II. LOCATION-AWARE COOPERATION-BASED SCHEME USING LINEAR NETWORK CODING

We consider an uplink problem of a wireless network consisting of N MUs $U_1, U_2, ..., U_N$ and a BS d (destination) as in Figure 1. Without loss of generality, we assume the MUs are numbered in the decreasing order of the distance to the BS. The purpose for $U_1, U_2, ..., U_N$ is to transmit a set of symbols $x_1, x_2, ..., x_N$ to the BS. Due to large scale fading in direct transmission, x_1 and x_N require the most and the least transmit power, respectively, to provide a comparable QoS.

This proposed scheme aims to provide distributed spatial diversity to the network to reduce the total transmit power while maintaining a low transmission delay. In this scheme, U_1 with farthest distance seeks help from all hopping terminals, U_2 with the second farthest distance seeks help from all hopping terminals other than U_1, and so on. U_N with closest

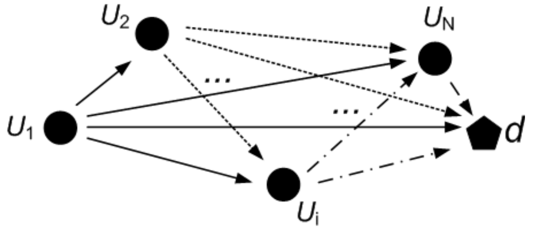

Fig. 1. A wireless network consisting of N mobile units $U_1, U_2, ..., U_N$ and a base station d.

distance operates under direct transmission mode. We consider both DAF and AAF protocols with the use of network coding at MUs to achieve this objective. Following are system models for the DAF and AAF protocols used in our proposed scheme.

A. DAF Linear Network Coding Protocol

Each MU U_i for $i = 2, 3, ..., N$ is allocated two time slots. In the first time slot, U_i applies a linear network coding on the overheard symbols $x_1, ..., x_{i-1}$ that it has successfully decoded previously to form a linearly coded version of these symbols and transmits it to d. In the second time slot, U_i transmits its own symbol x_i to $U_{i+1}, ..., U_N$ and d. U_1 has one time slot since it transmits its own symbol only. The total time slots required to transmit a set of N symbols is $(2N-1)$. In this proposed scheme, U_1 receives assistance from all MUs while U_N receives none; U_N operates in direct transmission mode. Figure 2 illustrates the transmission structure of the location-aware cooperative scheme. From this structure, we expect spatial diversity orders of $N, N-1, ..., 1$ allocated for $x_1, x_2, ..., x_N$, respectively.

To eliminate interference in the linearly coded version of the overheard symbols, each symbol x_j is protected by a signature waveform $s_j(t)$. The cross-correlation between $s_j(t)$ and $s_i(t)$ is $\rho_{ji} = < s_j(t), s_i(t) >$. Let $\widetilde{P}_{ij}^D$ ("D" for DAF) be the power allocated at U_i in delivery of x_j. Then [3]

$$\widetilde{P}_{ij}^D = \begin{cases} P_{ij} & \text{if } U_i \text{ decodes } x_j \text{ correctly} \\ 0 & \text{otherwise} \end{cases} . \quad (1)$$

Power allocation and detection at MUs acting as relays will be described later. Note that the total transmit power to deliver x_j is $P_j = \sum_{i=j}^{N} P_{ij}$. Also let h_{uv} be a generic channel coefficient representing the channel between any two nodes. h_{uv} is modeled as zero-mean circular symmetric complex Gaussian random variable with variance σ_{uv}^2. Consequently, the channel gain $|h_{uv}|$ is modeled as Rayleigh random variable [7]. Furthermore, the square of channel gain $|h_{uv}|^2$ is modeled as an exponential random variable with mean σ_{uv}^2, i.e., the probability density function (PDF) of $|h_{uv}|^2$ is [7] $f_{|h_{uv}|^2}\left(|h_{uv}|^2\right) = 1/\sigma_{uv}^2 \exp\left(-|h_{uv}|^2/\sigma_{uv}^2\right) U\left(|h_{uv}|^2\right)$, where $U(.)$ is the unit step function.

Based on these assumptions, the received signals at the destination from U_i in the first time slot, $y_{idr}^D(t)$ ("r" for relaying) and in the second time slot, $y_{ido}^D(t)$ ("o" for own) are

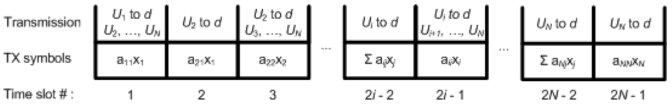

Fig. 2. Transmission structure of location-aware cooperative communication using linear network coding.

$$\begin{aligned} y_{idr}^D(t) &= h_{id} \sum_{j=1}^{i-1} \sqrt{\widetilde{P}_{ij}^D} x_j s_j(t) + n_{idr}^D(t), & (2) \\ y_{ido}^D(t) &= \sqrt{P_{ii}} h_{id} x_i s_i(t) + n_{ido}^D(t), & (3) \end{aligned}$$

respectively. Note that the received signal from U_1 follows (3) with $i = 1$. In (2) and (3), $n_{idr}^D(t)$ and $n_{ido}^D(t)$ are modeled as i.i.d. adaptive white Gaussian noise (AWGN) with power spectrum density N_0. Now we denote $a_{ij}^D = \sqrt{\widetilde{P}_{ij}^D} h_{id}$ for $i = 1, ..., N$ and $j = 1, ..., i-1$ and $a_{ii}^D = \sqrt{P_{ii}} h_{id}$ as signal coefficients and rewrite (2) and (3) as

$$\begin{aligned} y_{idr}^D(t) &= \sum_{j=1}^{i-1} a_{ij}^D x_j s_j(t) + n_{idr}^D(t), & (4) \\ y_{ido}^D(t) &= a_{ii}^D x_i s_i(t) + n_{ido}^D(t), & (5) \end{aligned}$$

respectively.

B. AAF Linear Network Coding Protocol

The difference between AAF and DAF protocols is that instead of decoding and re-encoding the overheard symbols in the first time slot, U_i simply amplifies the overheard signals and forwards a linearly coded version of these signals to d. In the second time slot, U_i also transmits its own symbol x_i to $U_{i+1}, ..., U_N$ and d. Other assumptions for DAF protocol remain the same in AAF protocol.

The received signals at the destination from U_i for $i = 2, ..., N$ in the first time slot, $y_{idr}^A(t)$ ("A" for AAF) and the second time slot, $y_{ido}^A(t)$ are

$$y_{idr}^A(t) = h_{id} \sum_{j=1}^{i-1} \frac{\sqrt{P_{ij}}}{\sqrt{P_{jj}|h_{ji}|^2 + N_0}} y_{jio}(t) + n_{idr}^A(t), \quad (6)$$

where

$$y_{jio}^A(t) = \sqrt{P_{jj}} h_{ji} x_j s_j(t) + n_{jio}^A(t) \quad (7)$$

for $j = 1, ..., i-1$, and

$$y_{ido}^A(t) = \sqrt{P_{ii}} h_{id} x_i s_i(t) + n_{ido}^A(t), \quad (8)$$

respectively. Note that the received signal from U_1 follows (8) with $i = 1$. In (6) - (8), $n_{idr}^A(t)$, $n_{jio}^A(t)$, and $n_{ido}^A(t)$ are modeled as i.i.d. AWGN with power spectral density N_0.

Let us take a close look at the signal $y_{idr}^A(t)$. Substituting (7) into (6), we have

$$y_{idr}^A(t) = h_{id} \sum_{j=1}^{i-1} \frac{\sqrt{P_{ij} P_{jj}} h_{ji}}{\sqrt{P_{jj}|h_{ji}|^2 + N_0}} x_j s_j(t)$$

$$
\begin{aligned}
&+\quad h_{id}\sum_{j=1}^{i-1}\frac{\sqrt{P_{ij}}}{\sqrt{P_{jj}|h_{ji}|^2+N_0}}\ n_{jio}(t)+n_{idr}^{A}(t)\\
&=\quad \sum_{j=1}^{i-1}a_{ij}^{A}x_j s_j(t)+\widetilde{n}_{idr}^{A}(t),
\end{aligned}
\tag{9}
$$

where we denote $a_{ij}^{A}=\sqrt{\widetilde{P}_{ij}^{A}}h_{id}$ as a signal coefficient from U_i in association with x_j with

$$
\widetilde{P}_{ij}^{A}=\frac{P_{ij}P_{jj}|h_{ji}|^2}{P_{jj}|h_{ji}|^2+N_0},
\tag{10}
$$

and the noise $\widetilde{n}_{idr}^{A}(t)$ with power spectral density $N_0 f_i$,

$$
f_i=\sum_{j=1}^{i-1}\frac{P_{ij}|h_{id}|^2}{P_{jj}|h_{ji}|^2+N_0}+1
\tag{11}
$$

a factor representing the noise amplification impact at U_i. Likewise, we denote $a_{ii}^{A}=\sqrt{P_{ii}}h_{id}$ and rewrite (8) as

$$
y_{ido}^{A}(t)=a_{ii}^{A}x_i s_i(t)+n_{ido}^{A}(t).
\tag{12}
$$

C. A General Form for DAF and AAF Protocols

We see that DAF and AAF protocols share the same system models with different parameters. In general, the transmit signals from U_i in the first and the second time slot are

$$
y_{idr}(t)\ =\ \sum_{j=1}^{i-1}a_{ij}x_j s_j(t)+n_{idr}(t),
\tag{13}
$$

$$
y_{ido}(t)\ =\ a_{ii}x_i s_i(t)+n_{ido}(t),
\tag{14}
$$

respectively. In the above equations, $a_{ii}=\sqrt{P_{ii}}h_{id}$, $a_{ij}=\sqrt{\widetilde{P}_{ij}}h_{id}$ for $i=1,...,N$ and $j=1,...,i-1$ where $\widetilde{P}_{ij}$ follows (1) for DAF and (10) for AAF, and the power spectral density of $n_{ido}(t)$ and $n_{idr}(t)$ is N_0 and $N_i=N_0 f_i$, respectively, where

$$
f_i=\begin{cases}1 & \text{for DAF}\\ \sum_{j=1}^{i-1}\frac{P_{ij}|h_{id}|^2}{P_{jj}|h_{ji}|^2+N_0}+1 & \text{for AAF}\end{cases}.
\tag{15}
$$

III. DATA DETECTION AT BASE STATION

In this section, we use multiuser detection at the BS for our proposed scheme. Data detection is performed by first applying matched-filtering to the received signals with respect to signature waveforms. Then multiuser detection is followed to obtain a set of desired symbols.

A. Matched Filtering

Given the system models in Section II, the BS receives N direct transmissions in the odd time slots and $(N-1)$ relaying transmissions in the even ones. Matched-filtering with respect to signature waveforms is applied to the received signals to produce a total of $M=\frac{N(N+1)}{2}$ discrete-time signals of the form

$$
y_{idj}=<y_{idr}(t),s_j(t)>=a_{ij}x_j+\sum_{k=1;k\neq j}^{i-1}a_{ik}\rho_{jk}x_k+n_{idj},
\tag{16}
$$

$$
y_{idi}=<y_{ido}(t),s_i(t)>=a_{ii}x_i+n_{idi}
\tag{17}
$$

for $i=1,...,N$ and $j=1,...,i-1$. In (16) and (17), $n_{idi}\sim\mathcal{N}(0,N_0)$ and $n_{idj}\sim\mathcal{N}(0,N_0 f_i)$ are the AWGN.

Let $\mathbf{y}=[y_{1d1},y_{2d1},...,y_{idj},...,y_{NdN}]^T$ be the received signal vector and $\mathbf{R}_i=<\mathbf{s}_i,\ \mathbf{s}_i^T>$ be the cross-correlation matrix where $\mathbf{s}_i=[s_1(t),s_2(t),...,s_i(t)]^T$. We can write

$$
\mathbf{y}=\mathbf{RAx}+\mathbf{n},
\tag{18}
$$

where $\mathbf{x}=[x_1,x_2,...,x_N]^T$, $\mathbf{R}=\mathrm{diag}\{1,\mathbf{R}_1,1,...,\mathbf{R}_i,1,...,\mathbf{R}_{N-1},1\}_{M\times M}$, and

$$
\mathbf{A}=\begin{bmatrix}
\mathrm{diag}(a_{11}) & \mathbf{0}_{1\times(N-1)}\\
\mathrm{diag}(a_{21},a_{22}) & \mathbf{0}_{2\times(N-2)}\\
\ddots & \vdots\\
\mathrm{diag}(a_{i1},...,a_{ij},...,a_{ii}) & \mathbf{0}_{i\times(N-i)}\\
\ddots & \vdots\\
\mathrm{diag}(a_{N1},...,a_{Nj},...,a_{NN}) &
\end{bmatrix}_{M\times N}.
$$

Also in (18), $\mathbf{n}\sim\mathcal{N}(\mathbf{0},N_0\widetilde{\mathbf{R}})$ where $\widetilde{\mathbf{R}}=\mathrm{diag}\left\{1,\widetilde{\mathbf{R}}_1,1,...,\widetilde{\mathbf{R}}_{i-1},1,...,\widetilde{\mathbf{R}}_{N-1},1\right\}$ with $\widetilde{\mathbf{R}}_{i-1}=f_i\mathbf{R}_{i-1}$. If we let $\mathbf{F}=\mathrm{diag}\left\{1,f_2,1,...,\underbrace{f_i,...,f_i}_{\text{(i−1)times}},1,...,1\right\}$, then $\widetilde{\mathbf{R}}=\mathbf{FR}$.

B. Multiuser Detection Scheme

Assume $\mathbf{R}_i$ is invertible with the invert matrix $\mathbf{R}_i^{-1}$. Then the inverse of $\mathbf{R}$ exists with $\mathbf{R}^{-1}=\mathrm{diag}\left\{1,\mathbf{R}_1^{-1},1,...,\mathbf{R}_{i-1}^{-1},1,...,\mathbf{R}_{N-1}^{-1},1\right\}$. Multiuser detection is applied to the received signal vector in two steps. First the vector $\mathbf{y}$ is pre-multiplied with the inverse $\mathbf{R}^{-1}$ to obtain

$$
\widetilde{\mathbf{y}}=\mathbf{R}^{-1}\mathbf{y}=\mathbf{Ax}+\widetilde{\mathbf{n}},
\tag{19}
$$

where $\widetilde{\mathbf{n}}\sim\mathcal{N}(\mathbf{0},N_0\mathbf{R}^{-1}\mathbf{F})$. Then $\widetilde{\mathbf{y}}$ is grouped into signal vectors $\mathbf{y}_j$ in association with the desired symbols x_j as

$$
\mathbf{y}_j=\mathbf{a}_j x_j+\mathbf{n}_j,
\tag{20}
$$

where $\mathbf{a}_j=[a_{jj},...,a_{ij},...,a_{Nj}]^T$ for $j=1,...,N$ and $i=j,...,N$ and $\mathbf{n}_j\sim\mathcal{N}(\mathbf{0},\mathbf{K}_j)$ in which $\mathbf{K}_j=N_0\,\mathrm{diag}\left\{1,...f_i(\mathbf{R}_{i-1}^{-1})_{jj},...,f_N(\mathbf{R}_{N-1}^{-1})_{jj}\right\}=\mathrm{diag}\left\{\sigma_{jj}^2,...,\sigma_{ij}^2,...,\sigma_{Nj}^2\right\}$. It can be shown that for the case $\rho_{ji}=\rho$ for all $i\neq j$, $r_i\triangleq\left(\mathbf{R}_{i-1}^{-1}\right)_{jj}=\frac{1+(i-3)\rho}{(1-\rho)(1+(i-2)\rho)}$ [8], independent of j. Thus

$$
\sigma_{ij}^2=N_0\begin{cases}1 & \text{if } i=j\\ f_i r_i & \text{if } j<i\leq N\end{cases},
\tag{21}
$$

where f_i follows (15). Note that r_i in (21) represents the cross-correlation impact due to the sum of transmit signals from U_i.

Let $\mathbf{b}_j=\left[\frac{a_{jj}}{\sigma_{jj}^2},...,\frac{a_{ij}}{\sigma_{ij}^2},...,\frac{a_{Nj}}{\sigma_{Nj}^2}\right]^T$. Then the desired symbol is detected as

$$
\hat{x}_j=\mathbf{b}_j^H\mathbf{y}_j=a_j x_j+n_j,
\tag{22}
$$

where $a_j=\mathbf{b}_j^H\mathbf{a}_j=\sum_{i=j}^{N}\frac{|a_{ij}|^2}{\sigma_{ij}^2}$, and $n_j=\mathbf{b}_j^H\mathbf{n}_j\sim\mathcal{N}\left(0,\sigma_j^2\right)$ with $\sigma_j^2=\sum_{i=j}^{N}\frac{|a_{ij}|^2}{\sigma_{ij}^2}$. Thus for BPSK modulation, the detection rule is

$$
\hat{x}_j=\mathrm{sgn}\left\{\mathbf{b}_j^H\mathbf{y}_j\right\}.
\tag{23}
$$

C. Detection at Mobile Units for DAF Protocol

In DAF, MUs decode the overheard symbols, re-encodes, and forwards it to the BS. To re-encode the symbols, a MU is assumed to know all signature waveforms from MUs before it, and this knowledge is used to detect the overheard symbols. At U_i, matched-filtering is applied to the received signal $y^D_{jio}(t)$ produce the desired symbol x_j as

$$y_{j,u_i} =< y^D_{jio}(t), s_j(t) >= \sqrt{P_{jj}} h_{ji} x_j + n_{j,u_i}, \qquad (24)$$

where $n_{j,u_i} \sim \mathcal{N}(0, N_0)$. Thus for BPSK modulation, the detection rule is

$$\widehat{x}_{j,u_i} = \operatorname{sgn}\left\{< y^D_{jio}(t), s_j(t) >\right\}. \qquad (25)$$

Note that only a simple detection is used at MUs.

IV. PERFORMANCE ANALYSIS

In this section, we analyze the performance of our proposed scheme that is introduced in Section II. The detection in (23) provides the maximal instantaneous signal-to-interference-plus-noise ratio (SINR) γ_j corresponding to the desired symbol x_j as

$$\gamma_j = \sum_{i=j}^{N} \frac{|a_{ij}|^2}{\sigma^2_{ij}} = \frac{P_{jj}|h_{jd}|^2}{N_0} + \sum_{i=j+1}^{N} \frac{\widetilde{P}_{ij}|h_{id}|^2}{f_i r_i N_0}, \qquad (26)$$

and (26) will be used to provide BER expressions for DAF and AAF protocols.

A. BER Expression for DAF Protocol

Let β_{ij} for $i = j+1, ..., N$ be a binary number representing the detection correctness at U_i in detecting x_j. Then β_{ij} is a Bernoulli random variable, which is distributed as

$$\beta_{ij} = \begin{cases} 1 & \text{w.p. } 1 - p_{j,u_i} \\ 0 & \text{w.p. } p_{j,u_i} \end{cases}, \qquad (27)$$

where p_{j,u_i} is the BER in detection of x_j at U_i. For each information x_j, the β_{ij}'s form a decimal number $S_j = \beta_{(j+1)j}...\beta_{ij}...\beta_{Nj}$, which represents one of $\left(2^{(N-j)}\right)$ detection states of these $(N-j)$ MUs acting as relays.

Based on (25), the conditional BER of detecting x_j at U_i can be written as [9]

$$p^{h_{ji}}_{j,u_i} = Q\left(\sqrt{\gamma_{j,u_i}}\right) = \frac{1}{\pi}\int_0^{\pi/2} \exp\left(-\frac{\gamma_{j,u_i}}{2\sin^2\theta}\right) d\theta, \qquad (28)$$

where $\gamma_{j,u_i} = P_{jj}|h_{ji}|^2/N_0$ is the instantaneous signal-to-noise ratio (SNR) at U_i in detection of x_j. By averaging (28) with respect to the exponential random variable $|h_{ji}|^2$, the unconditional BER is calculated as

$$p_{j,u_i} = F\left(1 + \frac{P_{jj}\sigma^2_{ji}}{2N_0\sin^2\theta}\right), \qquad (29)$$

where

$$F\left(x(\theta)\right) = \frac{1}{\pi}\int_0^{\pi/2} \frac{1}{x(\theta)} d\theta. \qquad (30)$$

Thus the transmit power $\widetilde{P}^D_{ij}$ allocated at U_i to deliver x_j for $i = 2, ..., N$ and $j = 1, ..., i-1$ can be expressed as $\widetilde{P}^D_{ij} = P_{ij}\beta_{ij}$.

Now, the instantaneous SINR γ^D_j at the destination can be expressed as

$$\gamma^D_j = \frac{P_{jj}|h_{jd}|^2}{N_0} + \sum_{i=j+1}^{N} \frac{P_{ij}\beta_{ij}|h_{id}|^2}{r_i N_0}, \qquad (31)$$

where we have used $f_i = 1$ for DAF. Based on (31), it can be shown that the BER in detecting x_j at the BS is [3]

$$\begin{aligned} p^D_j \;=\; & \sum_{S_j=0}^{2^{(N-j)}-1} F\left(\left(1 + \frac{P_{jj}\sigma^2_{jd}}{2N_0\sin^2\theta}\right)\right. \\ & \times \left.\prod_{i=j+1}^{N}\left(1 + \frac{P_{ij}\beta_{ij}\sigma^2_{id}}{2r_i N_0\sin^2\theta}\right)\right) \prod_{i=j+1}^{N} G\left(\beta_{ij}\right) \qquad (32) \end{aligned}$$

where

$$G\left(\beta_{ij}\right) = \begin{cases} 1 - p_{j,u_i} & \text{if } \beta_{ij} = 1 \\ p_{j,u_i} & \text{if } \beta_{ij} = 0 \end{cases} \qquad (33)$$

and $F(.)$ follows (30). From (32), we expect that x_j will receive a spatial diversity order of $(N - j + 1)$.

B. BER Expression for AAF Protocol

The conditional BER for AAF protocol given the all channel coefficients is

$$p^{A,\{h_{id},h_{ji}\}}_j = Q\left(\sqrt{\gamma^A_j}\right). \qquad (34)$$

where γ^A_j follows (26) with f_i in (15) for AAF protocol. At the present time, it is difficult to obtain a close-form expression for f_i in term of the channel variances σ^2_{id} and σ^2_{ji}. Therefore, (34) will be used to provide numerical results to validate our proposed scheme.

V. NUMERICAL RESULTS

In this section, we perform computer simulations to validate our proposed scheme for both DAF and AAF protocols. In all simulations, the number of MUs $N = 4$ and the variance of the noise $N_0 = 1$. We assume all channel variances are 1, i.e., $\sigma^2_{id} = \sigma^2_{ji} = 1$ for $i = 1, ..., N$ and $j = 1, ...i-1$ and the total transmit powers $P_j = \sum_{i=j}^{N} P_{ij}$ corresponding to x_j are the same for j. Furthermore, we assume equal power allocation [3] for x_j for $j = 1, ..., N-1$, i.e.

$$P_{ij} = \begin{cases} \frac{P_j}{2} & \text{if } i = j \\ \frac{\frac{P_j}{2}}{2(N-j)} & \text{if } j < i \le N \end{cases}. \qquad (35)$$

For x_N, $P_{NN} = P_N$ since it is transmitted directly to the BS. We also assume that the cross-correlation $\rho_{ji} = \rho$ for all $i \neq j$. We use $\rho = 0.5$ in our simulations. The MUs are numbered in the reduction order of the distance to the BS; therefore, we expect a diversity order of 4, 3, 2, and 1 for x_1, x_2, x_3, and x_4.

Figures 3 and 4 present the analytical and simulation results for DAF protocol and the numerical and simulation results for

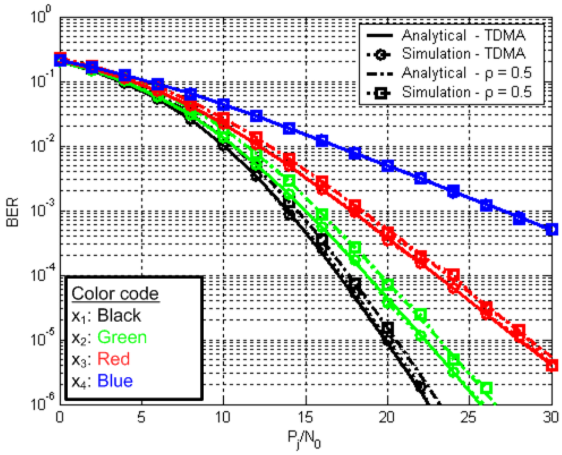

Fig. 3. BER versus SNR performance for DAF protocol - A comparison between the proposed scheme and the conventional TDMA scheme.

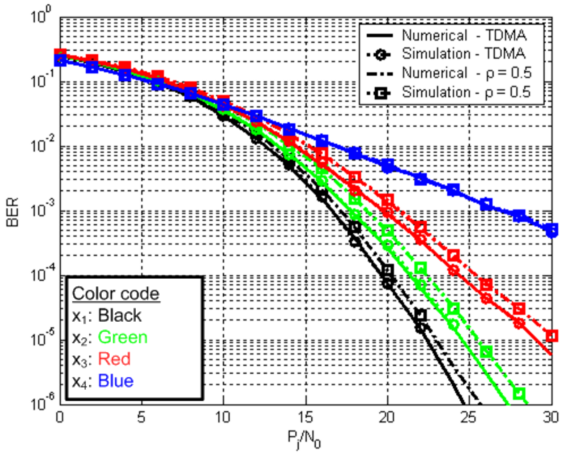

Fig. 4. BER versus SNR performance for AAF protocol - A comparison between the proposed scheme and the conventional TDMA scheme.

AAF protocol, respectively. The figures provide a comparison in term of BER performance between our proposed scheme and the conventional cooperation-based TDMA scheme. In each figure, BER versus SNR (P_j/N_0) performance for each information x_j is presented. Clearly, our proposed scheme provides the expected diversity orders in both DAF and AAF protocols. In other words, given the use of nonorthogonality, our proposed scheme still achieves full diversity. The diversity orders can be used to reduce the transmit power of distant MUs, given the same QoS with the closer ones. In addition, the figures show that for the case of $\rho = 0.5$, the performance gap is less than 1dB, given the same BER. This is significant because the delay in our proposed scheme is only $(2N-1)$, a substantial reduction in comparison with the conventional TDMA scheme, which results in a delay of $N(N+1)/2$.

Figure 5 provides a comparison between DAF and AAF protocols. From the figure, DAF protocol outperforms AAF protocol. In particular, there is about 2.5dB gap in performance between the two protocols. The figure also shows that the gap reduces as the diversity order decreases. DAF protocol outperforms AAF protocol because of the error propagation in AAF protocol. Nevertheless, both DAF and AAF protocols achieve full diversity in our scheme.

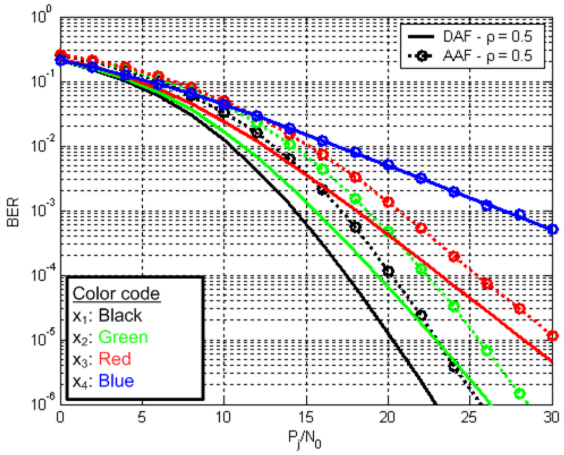

Fig. 5. BER versus SNR performance between DAF and AAF protocol $(\rho = 0.5)$.

VI. CONCLUSIONS

In this paper, we proposed a location-aware cooperation-based scheme using linear network coding, where each MU forms a linear coded version of all symbols it has received previously. The scheme aims to provide to distant MUs higher diversity orders, which can be used to reduce their transmit power. Multiuser detection is used at the BS to decouple the transmit symbols. Both DAF and AAF protocols were considered, performance analysis was presented, and simulations showed that our proposed scheme can achieve a comparable performance but with a substantial reduction in delay in comparison with the conventional cooperation-based TDMA scheme. The delay in our proposed scheme is only $(2N-1)$ for a network of N MUs while that is $N(N+1)/2$ in the conventional scheme.

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