Interference Decoding in Cellular Wireless Relay Networks with Space-Time Coding

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***Abstract*—In this paper we propose a cooperative protocol and a symbol decoding algorithm that target improved performance in the presence of inter-cell interference (ICI) in wireless cellular networks. Our scheme uses the wireless signals that interfere at relay nodes located at the cell edge instead of discarding them. The relays are non-regenerative and apply a space-time code (STC) to the interfered signal. Subsequently, the relays broadcast the coded signals. At the destinations the interfered and ST-coded signals are decoded in two stages. First by decoding the STC, and then by applying successive interference cancellation (SIC). Simulation results for Rayleigh fading channel reveal significant throughput benefits even in the low SNR regime. We also present results for a small-scale LTE-based cellular scenario and we compare our scheme against the Coordinated MultiPoint (CoMP) transmission mode of LTE-A that is based on beamforming.**

***Index Terms*—Interference decoding, cooperative protocol, Alamouti code, space-time block coding, distributed space-time coding, physical layer network coding, wireless networks, ICI, LTE-A.**

I. Introduction

Interference coordination has been recently proposed as an efficient mechanism to combat interference in advanced wireless cellular standards like the 3GPP UTRAN Long Term Evolution (LTE) [1]. LTE adopts a flat frequency reuse approach which means that all base stations (BS) can use the same frequency band. Thus, when two neighboring BSs schedule transmissions in the same frequency band interference is naturally present at the user equipment (UE). In advanced cellular standards like LTE this inter-cell interference (ICI) is handled with the mechanism of ICI coordination (ICIC) [1]. With ICIC when two neighboring BSs use the same orthogonal frequency-division multiple access (OFDMA) subcarrier during the same time slot (this is a single resource block in LTE terminology), then the BSs coordinate through the backhaul network in order to minimize the allocated power to these subcarriers leading thus to reduced interference. At the same time they can independently increase the allocated power to the remaining OFDMA subcarriers. This means that resource allocation between BSs is exercised in a cooperative fashion for UEs that are located at the cell edge.

But ICIC does not completely eliminate interference while in addition it requires coordination between the BSs through the backhaul network. A more efficient way to combat ICI is through the coordinated multipoint (CoMP) transmission scheme that is also adopted in LTE [2]. CoMP allows two or three neighboring BSs to transmit simultaneously to UEs residing at the cell edge. All BSs must have CSI for each point-to-point link that is created towards the UE. Subsequently, they can use beamforming in order to theoretically eliminate (or in practice minimize) interference. However, CoMP requires very low delay communication through the backhaul network in order to transmit the precoding vectors necessary for beamforming [3].

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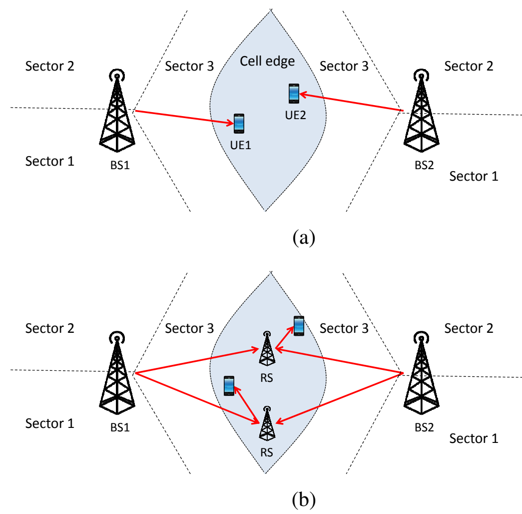


Fig. 1. (a) In LTE ICIC allows the BSs to coordinate the transmissions towards their respective destinations. (b) Application scenario of the proposed scheme in a cellular network where the two BSs transmit simultaneously towards their destinations in the same resource block. The relay nodes transmit in the next slot.

Besides the previous mechanisms that are specifically engineered for combating ICI, in LTE there is a provision for using relay nodes primarily for improving the received SNR at the UE [2]. In addition, the relays can also used for offering cooperative diversity benefits with the addition of distributed space-time codes (DSTC) [4]. *In this paper we want to investigate the potential for improving the cell-edge performance of UEs in the presence of ICI with the aid of these relay nodes. We consider the case that the BSs cannot coordinate and they do not have CSI availability at the transmitter like the CoMP transmission scheme.*

Relay nodes in a wireless network can be used in this uncoventional way, i.e. receive and forward interfering signals. One way to accomplish it is through the idea of physical layer network coding (PLNC) [5], [6]. PLNC is fundamentally an interference cancellation mechanism that is however based on the premise that there is a-priori information at the receivers [5], [6]. Multiple relays and their use for recovering from collisions reactively has also been studied in [7]. Another interesting recent idea for handling interference is ZigZag decoding that uses SIC for decoding the collision of one packet with itself when it is re-transmitted from an access point (AP) [8]. With ZigZag collision decoding is performed reactively and only with the available signals at the AP. Multi-user detection (MUD) represents a class of techniques that are specifically focused on separating interfering signal transmissions [9]. Due to the plethora of works in this area the interested reader is referred to the comprehensive overview of [10]. MUD with cooperative decode and forward relaying was studied in [11], [12]. MUD for CDMA cellular systems that includes also intermediate relays besides the base station was also studied in [12]. The maturity of the efforts in space-time coding (STC) and interference/MUD decoding allowed recently their joint consideration. In [13] distributed space-time coding (DSTC) has been combined with simultaneous multi-source transmission and interference cancellation. The authors considered a single relay that is equipped with several antennas while the number of antennas is equal to the number of concurrently transmitting sources. This approach effectively creates several point-to-point channels [3].

In this paper we propose a new form of distributed STC-based cooperation that improves interference decoding. Our scheme is named *Interference Decoding with Space-Time Coding (IDSTC)*. The central idea is to fully utilize collided[1] wireless signals by exploiting first the fact that these interfering signals are overheard at the relays. The fundamental communication topology in this paper involves source nodes, relays that receive the collided signals, and one or more destination nodes as seen in Fig. 2. The relays apply a STC to the interfering signals and then they simultaneously transmit to the destination. In an LTE scenario, the sources S_1, S_2 would be mapped to the BSs as depicted in Fig. 1.

II. System Model

In this paper matrices are denoted with bold capital letters, i.e. $\mathbf{A}$. Bold lowercase denote vectors. The matrices $\mathbf{A}^T$, $\mathbf{A}^H$, $\mathbf{A}^*$, are the transpose, Hermitian, and conjugate of $\mathbf{A}$. The notations $\|\cdot\|$, and $\|\cdot\|_F$ are the Euclidian and Frobenius norms, $\mathrm{Tr}(\cdot)$ is the trace of matrix, $\mathrm{vec}(\cdot)$ vectorizes a matrix, and $E[\cdot]$ is expectation of a random variable.

Our study considers a relay network model where each source in the set $\mathcal{S} \triangleq \{S_1, S_2, ..., S_N\}$ communicates with one or multiple destinations in the set $\mathcal{D} \triangleq \{D_1, D_2, ..., D_J\}$ with the assistance of the set of relays $\mathcal{R} \triangleq \{R_1, R_2, ..., R_M\}$. This is a multi-source multi-destination communication model. In Fig. 2 we present the network topology that we study in this paper and it includes the sources, the relays, and the destinations. Every node has a single omni-directional antenna that can be used both for transmission and reception while all nodes have the same average power constraint. We denote the channel from the s-th source to the r-th relay as $h_{s,r}$, and the channel from the r-th relay to destination d as $h_{r,d}$. We assume that the fading coefficients are independent and $h_{s,r} \sim \mathcal{CN}(0,1)$, $h_{r,d} \sim \mathcal{CN}(0,1)$, i.e. they are complex Gaussian random variables with zero mean and unit variance. All the channels, from sources to relays and relays to destinations are considered to be block-fading Rayleigh. The channel coefficients are quasi-stationary, that is they remain constant for the coherence period of the channel that is T symbols for each source/relay and relay/destination pair. Additive white Gaussian noise (AWGN) is assumed at the relays and the destinations. The packet length L is expressed in terms of symbols. Receiver channel state information (CSIR) at each destination is assumed to be available from the packet preambles.

To model the system behavior we introduce the concept of the *symbol slot* which is the basic time unit that we consider in this paper and it corresponds to the transmission time of a physical layer (PHY) symbol. A *transmission phase* is a system defined parameter and denotes the time period where a user (source or relay) can transmit a packet and it consists of many symbol slots. This is essentially similar to a TDMA slot but in our system multiple sources can transmit during the same transmission phase and interfere their symbols.

[1]In this paper we use interchangeably the terms interfering signals and collisions to refer to the same fundamental event.

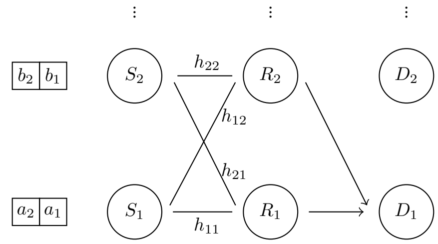


Fig. 2. Fundamental two-hop topology that includes multiple sources, relays and destinations. In the sample packets depicted on the left of the figure each source transmits two symbols successively. Any equal number of sources and relays can be supported by the system model.

DSTC Protocol				
Node/Slot	t_1	t_2	t_3	t_4
S_1	a_1	a_2		
R_1			a_1h_{11}	$-(a_2h_{11})^*$
R_2			a_2h_{12}	$(a_1h_{12})^*$
IDSTC Protocol				
Node/Slot	t_1	t_2	t_3	t_4
S_1	a_1	a_2		
S_2	b_1	b_2		
R_1			$a_1h_{11} + b_1h_{21}$	$-(a_2h_{11} + b_2h_{21})^*$
R_2			$a_2h_{12} + b_2h_{22}$	$(a_1h_{12} + b_1h_{22})^*$

TABLE I
Behavior in the time domain of the DSTC and IDSTC protocols for the topology depicted in Fig. 2.

III. IDSTC Protocol Description

The behavior of the protocol in the time domain can be seen in Table I for the topology of two sources and two relays that was presented in Fig. 2. The transmission of a packet requires two hops since we assume that there is no viable direct link between the sources and the destinations. With the proposed protocol the cooperative packet transmission requires two phases. The first phase is the broadcast transmission phase, where all the source nodes broadcast their packets. At the M relays the interfered symbol is spread in space (over the M relays) and in time (over T symbol durations). A relay does not require any knowledge regarding the received signals at the other relays since it only applies a specific STC coefficient to each interfered symbol as we will later see. Our model allows for the case that $M > N$ which means that relay selection is possible if more relays are available. The relays transmit the coded interfered signals simultaneously, and finally they are decoded at each destination. The interfered symbols can be coded with an orthogonal STC or a general linear dispersion (LD) code [4].

A. Source to Relay Transmission Phase

Let $x_s[t]$ denote the complex symbol that source s wants to transmit during the symbol slot t. These are the information symbols and are expressed as an array

$$\mathbf{X}_{\mathcal{S}} = \begin{bmatrix} x_1[1] & \dots & x_1[t] & \dots & x_1[T] \\ \dots & \dots & \dots. & \dots & \dots \\ x_s[1] & \dots & x_s[t] & \dots & x_s[T] \\ \dots & \dots & \dots & \dots & \dots \\ x_N[1] & \dots & x_N[t] & \dots & x_N[T] \end{bmatrix}.$$

An amount of energy equal to ρ is allocated to the transmission of $\mathbf{X}_{\mathcal{S}}$ in order to compare fairly systems with different number of sources N and channel coherence time T. The energy normalization in this case corresponds first to $\sum_{s=1}^{N}\sum_{t=1}^{T}|x_s[t]|^2 = TN$. Therefore, during the first communication phase that is described here, and from symbol slot 1 to T, a source $s \in \mathcal{S}$ transmits the signal $\sqrt{\frac{\rho}{TN}}x_s[t]$ that is a part of larger packet. With $w_r[t]$ we denote the sample of the AWGN during symbol slot t, and $\mathbf{h}_{\mathcal{S},r} \in \mathbb{C}^{1\times N}$ is the channel matrix that contains the N channel gains from the first broadcast phase, i.e. from the sources $\mathcal{S}$ to relay r:

$$\mathbf{h}_{\mathcal{S},r} = [h_{1,r} \;\; h_{2,r} \; \dots \; h_{N,r}]$$

Now we can write in a compact form and with a vector notation the received signal at the relay during one symbol slot as

$$q_r[t] = \sqrt{\frac{\rho}{TN}}\mathbf{h}_{\mathcal{S},r}\mathbf{x}_{\mathcal{S}}[t] + w_r[t],$$

where $\mathbf{x}_{\mathcal{S}}[t] \in \mathbb{C}^{N\times 1}$ is a column vector of the matrix $\mathbf{X}_{\mathcal{S}}$. The relay does not have a decodable signal[2] and so it cannot construct a STC for a specific symbol $x_s[t]$. Instead, the relay constructs a STC for an interfered signal that is a linear combination of several symbols.

[2]The relay can decode with ML, SIC, or an efficient sphere decoder but still the high BER makes this approach impractical.

B. Relay Operation

With IDSTC we design the transmit signal at every relay r as a linear combination of the received over-the-air interfered symbol q_r. This is done for each symbol while there are in total L symbols for a packet. The relay also applies the power scaling factor g_r so as to maintain the power constraint. If an orthogonal STBC is used, or a more general LD code, the transmitted signal will be described in the following $M \times T$ matrix:

$$\mathbf{Z}_r = g_r\sum_{t=1}^{T}(\mathbf{A}_{r,t}q_r[t] + \mathbf{B}_{r,t}q_r^*[t]) \tag{1}$$

The r-th row of $\mathbf{Z}_r$ is what the r-th relay transmits in each of the T forwarding symbols slots. $\mathbf{A}_{r,t}, \mathbf{B}_{r,t}$ are the $M \times T$ STC matrices. They are further broken down as

$$\mathbf{A}_{r,t} = [\mathbf{0}_{T\times 1}, \dots, \mathbf{a}_{r,t}, \dots, \mathbf{0}_{T\times 1}]^T,$$

where $\mathbf{a}_{r,t}$ is a $T \times 1$ column vector specific for relay r while similar definition holds for $\mathbf{B}$. The contents of these matrices are 0 or 1 values that indicate whether during transmission slot t the relay r transmits the interfered symbol or not (or its complex conjugate for the case of $\mathbf{B}$). All the M relays transmit similarly in their corresponding transmission phase.

What this expression demonstrates, is that a symbol to be transmitted in a forwarding slot, is a linear combination of all the received symbols in the previous T symbol slots. This process is also visible in Table I where the creation process of the ST-coded interfered signal is depicted.

Let us elaborate on (1) and re-write it as:

$$\begin{aligned} \mathbf{Z}_r &= \sqrt{\frac{\rho}{TN}}g_r\sum_{t=1}^{T}\sum_{s=1}^{N}(h_{s,r}\mathbf{A}_{r,t}x_s[t] + h_{s,r}^*\mathbf{B}_{r,t}x_s^*[t]) \\ &+ g_r\sum_{t=1}^{T}(\mathbf{A}_t w_r[t] + \mathbf{B}_t w_r^*[t]) \end{aligned}$$

At one destination d, the received signal $\mathbf{y}_d \in \mathbb{C}^{1\times T}$ from all the relays over the T symbols slots will then be

$$\begin{aligned} \mathbf{y}_d &= \sqrt{\frac{\rho}{TN}}\Big(\sum_{t=1}^{T}\sum_{s=1}^{N}\sum_{r=1}^{M}g_r\mathbf{h}_{r,d}(\mathbf{A}_{r,t}h_{s,r}x_s[t] \\ &+ \mathbf{B}_{r,t}h_{s,r}^*x_s^*[t]) + \sum_{t=1}^{T}\sum_{r=1}^{M}g_r\mathbf{h}_{r,d}(\mathbf{A}_{r,t}w_r[t] \\ &+ \mathbf{B}_{r,t}w_r^*[t])\Big) + \mathbf{w}_d, \end{aligned} \tag{2}$$

where $\mathbf{h}_{r,d} \in \mathbb{C}^{1\times M}$ contains the channel gains from all the relays to the destination and it remains unchanged according to our stated assumptions. Also $\mathbf{w}_d \in \mathbb{C}^{1\times T}$ contains the noise samples at the final destination. The previous expression is important since it demonstrates that with this formulation and system design, we are able to express the signal at the destination as a function of the transmitted signal from the sources and not just that of the interfered signal at the relay. For easier manipulations in the decoding algorithm, from (2) we extract the noise vector at the final destination that consists of the amplified noise from the relays and the AWGN:

$$\mathbf{w}_{r,d} = g_r \mathbf{h}_{r,d} \sum_{t=1}^{T} (\mathbf{A}_{r,t} w_r[t] + \mathbf{B}_{r,t} w_r^*[t]) + \mathbf{w}_d \qquad (3)$$

IV. Decoding Algorithm

The proposed scheme can work with an arbitrary LD code expressed through the matrices $\mathbf{A}, \mathbf{B}$. However, for keeping the analysis simple and for demonstrating the main concept of the decoding algorithm more clearly, we assume that the ST code is orthogonal. Based on this choice, we present a new decoding algorithm that combines the decoding of general orthogonal designs and SIC for decoding interfered symbols. To proceed with the description of the decoding process, let us first define an extended form of the signal that is received during the forwarding phase that includes its complex conjugate as follows

$$\tilde{\mathbf{y}}_d = \left[\begin{array}{cccc} y_d[1] & \ldots & y_d[T] & y_d^*[1] \ldots & y_d^*[T] \end{array} \right]. \qquad (4)$$

The primary ML decision problem we desire to solve is equivalent to minimizing the squared Euclidean distance metric. From (2) and (4) we have that this ML metric is:

$$\begin{aligned} e &= \Bigg\| \tilde{\mathbf{y}}_d - \sqrt{\frac{\rho}{TN}} \sum_{t=1}^{T} \sum_{s=1}^{N} \sum_{r=1}^{M} g_r \Bigg(\left[\begin{array}{c} \mathbf{h}_{r,d} \mathbf{A}_{r,t} h_{s,r} \\ \mathbf{h}_{r,d}^* \mathbf{B}_{r,t}^* h_{s,r} \end{array} \right]^T x_s[t] \\ &+ \Big[\mathbf{h}_{r,d} \mathbf{B}_t h_{s,r}^* \quad \mathbf{h}_{r,d}^* \mathbf{A}_t^* h_{s,r}^* \Big] x_s^*[t] \Bigg) \Bigg\|^2 \qquad (5) \end{aligned}$$

The decoding expression of (5) can be simplified to:

$$\begin{aligned} e &= \Big((1 - 2MTN) \|\tilde{\mathbf{y}}_d\|^2 \Big) + 2 \sum_{t=1}^{T} \sum_{r=1}^{M} \sum_{s=1}^{N} \Big\| \tilde{\mathbf{y}}_d \qquad (6) \\ &- g_r \sqrt{\frac{\rho}{TN}} \Big[\mathbf{h}_{r,d} \mathbf{A}_{r,t} h_{s,r} \quad \mathbf{h}_{r,d}^* \mathbf{B}_{r,t}^* h_{s,r} \Big] x_s[t] \Big\|^2 \end{aligned}$$

At this stage, we have a simpler expression for the ML metric. We still have to relate it to the decoding of interfered symbols. One of the key ideas of the decoding algorithm is to employ matched filtering for each symbol that was transmitted at each source. Thus, we have that the sufficient statistic we can get for each symbol after matched filtering is

$$\begin{aligned} u_{s,t} &= \operatorname{Tr} \Big(\sum_{r=1}^{M} g_r \Big[\mathbf{h}_{r,d} \mathbf{A}_{r,t} h_{s,r} \quad \mathbf{h}_{r,d}^* \mathbf{B}_{r,t}^* h_{s,r} \Big]^H \tilde{\mathbf{y}}_d \Big) \\ &= \sum_{r=1}^{M} h_{s,r}^* g_r \Big(\mathbf{A}_{r,t}^H \mathbf{h}_{r,d}^H \mathbf{y}_d + \mathbf{y}_d^H \mathbf{h}_{r,d} \mathbf{B}_{r,t} \Big). \end{aligned}$$

Due to the orthogonal property of the STBCs we have that by using (2), $u_{s,t}$ becomes

$$\begin{aligned} u_{s,t} &= \sum_{r=1}^{M} \frac{h_{s,r}^* g_r^2 \|\mathbf{h}_{r,d}\|^2 \rho}{TN} \Big\{ \operatorname{Tr} \Big(\mathbf{A}_{r,t}^H \mathbf{A}_{r,t} + \mathbf{B}_{r,t}^H \mathbf{B}_{r,t} \Big) \\ &\times \sum_{n=1}^{N} h_{n,r} x_n[t] + \operatorname{Tr} \Big((\mathbf{A}_{r,t}^H \mathbf{A}_{r,t} + \mathbf{B}_{r,t}^H \mathbf{B}_{r,t}) w_r[t] \\ &+ \mathbf{A}_{r,t}^H \mathbf{h}_{r,d}^H \mathbf{w}_d + \mathbf{w}_d^H \mathbf{h}_{r,d} \mathbf{B}_{r,t} \Big) \Big\}. \qquad (7) \end{aligned}$$

This last expression shows that matched filtering for a symbol transmitted during slot t, decouples all the other symbols that were transmitted during any of the remaining symbol slots from a particular source.

After obtaining the sufficient statistic $u_{s,t}$ for each specific information symbol $x_s[t]$, the algorithm must account for the fact that $u_{s,t}$ contains a combination of all the other symbols that were transmitted in the specific symbol slot t. We provide a description of the ordered SIC (OSIC) algorithm to avoid further mathematical notation. If we denote by $\bar{\mathbf{y}}$ the ordered version from higher to lower power[3] of the received signals contained in $\tilde{\mathbf{y}}$ then we can apply the OSIC approach. The destination detects the highest power symbol first. Then with the use of the channel estimate this symbol is removed from $\bar{\mathbf{y}}$ and then the sufficient statistic for the next symbol is recalculated again from (7). This process of interference removal and detection continues until all the symbols from the N sources are decoded.

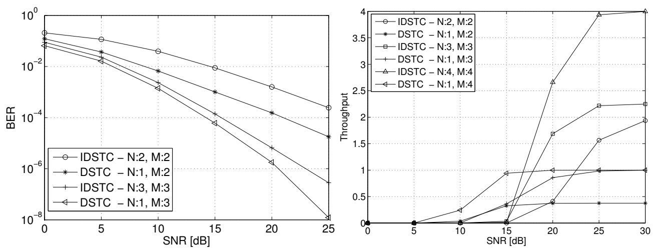
V. Performance Evaluation

A. Evaluation of the Basic Scheme for Rayleigh Fading

Simulation Parameters. We implemented the proposed cooperative scheme and we evaluated its performance in terms of BER and throughput under different channel conditions through Monte Carlo simulations for the topology of Fig. 2. This is in order to evaluate the performance of the decoding algorithm. We also implemented the DSTC protocol, where transmissions occur orthogonally/independently from each source and without being interfered [4]. With DSTC each relay applies the distributed STC without decoding the signals, while all the relays broadcast simultaneously. The received signals are combined and decoded with linear processing at each destination. The STC matrices are exactly the same for the DSTC and IDSTC systems. We present the averaged results for 2000 packet transmissions that have a length of 1000 bits while BPSK modulation was used. The channel bandwidth is 10 MHz, while a Rayleigh fading wireless channel model was employed. Furthermore, we also assume that the noise over the wireless spectrum is AWGN with the variance of the noise to be 10^{-9} W/Hz at every node/link. The channel transfer functions between the nodes vary independently but they are characterized by the same average SNR.

Results. The related results for symmetric channel conditions can be seen in Fig. 3. For N=2 sources and M=2 relays an Alamouti-type of code was employed by the relays when IDSTC and DSTC were employed. When we compare the configuration of N=2 sources with the case of N=3 sources we observe that the DSTC scheme already performs considerably better in terms of BER since additional nodes are used for creating the distributed code. On the other hand, the impact of IDSTC on the throughput is significant due to the increased number of transmissions per slot. Even though IDSTC performs slightly worse when compared to DSTC in terms of

[3]This ordering is easily accomplished through the channel estimation process.



(a) BER (b) Throughput

Fig. 3. Results for different number of sources N and all $|h_{x,y}| = 1$.

Parameter	Setting
Deployment	2 BS with 3 sectors, 2 RS
Downlink BS and RS TX power	46dBm and 34dBm
Inter-site distance (ISD)	500m
Carrier freq. / bandwidth	10MHz
air interface	Time-Division Duplex (TDD)
Fading	Rayleigh
Distance-dependent path loss	loss L=I + 37.6log10(.R), R in km, I=128.1 [1]
Shadowing standard deviation	8 dB
UE speed	3 kmph (quasi-static)
Traffic model	Infinite full buffer
Channel estimation	Ideal
User distribution	Uniform within each cell

TABLE II
CELLULAR NETWORK SIMULATION PARAMETERS.

BER the important behavior we want to stress at this point is that the performance is significantly improved as the number of sources/relays is increased. This is an important result and is actually a reversal in the performance trend when compared to PLNC [14], i.e. the BER is now minimized when more sources interfere their signals. The reason is that the diversity benefits from the use of the STC increase significantly the decoding performance of interfering signals at the receiver. The final result of all the above is that IDSTC outperforms significantly DSTC even in lower SNR regime in terms of throughput since now more sources transmit simultaneously. Another final aspect that we must comment is that the selected code for three sources is not a full-rate code but it is orthogonal while for four sources it is a full-rate orthogonal code. So the issue with the code used for N=3 is that the number of transmitted symbols is three in four slots and so the data rate is considerably quite lower when compared to the code for N=4.

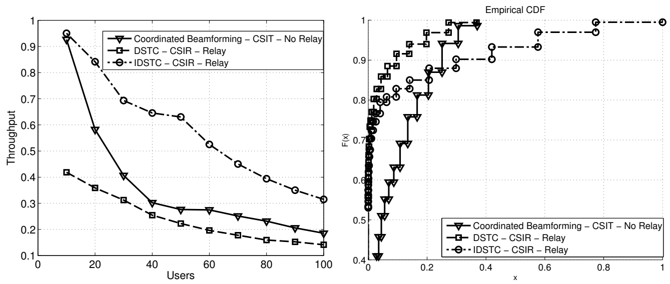
B. Evaluation for a Cellular LTE-based Scenario

Simulation Parameters. In this second part of our evaluation we considered the topology of Fig. 1. The parameters settings for this LTE-based simulation can be seen in Table II. In this case we tried to incorporate LTE parameters that are relevant for demonstrating the viability of our scheme and we did not try to be exhaustive with all the LTE details.

In the first system we considered cooperative beamforming (CB) with zero forcing at the BS while no cooperation is employed through relays. As we explained earlier, with CB the two BSs schedule their transmissions simultaneously so that interference is nulled to the other user. This system requires CSIT and we assume that this process is taking place perfectly through the backhaul network. This configuration simulates the behavior of CoMP in LTE. In the next two systems we employ in addition to the BSs two relays in the middle sector as seen in Fig. 1(b) while we only assume CSIR availability. More specifically, in the second system we consider the use of ICIC as we described it in the Introduction. This means that the BSs ensure that they do not transmit simultaneously in the same OFDMA resource block. In addition, when a BS transmits to a UE located in the middle sector, it uses the relays in conjunction with DSTC for improving the diversity gain. The third system implements the proposed idea: The BSs use ICIC again for all transmissions that are not targeted to the central sector in order to minimize interference. However, when the BSs want to transmit packets to UEs located in the the central sector, they do it in the same resource block, i.e. our system allows them to interfere their transmissions.

Results. We present the results for the average normalized per UE throughput vs. the number of UEs for a number of 200 resource blocks that we assume are available to the two BSs. The proposed system offers significantly better throughput than both the other two systems as Fig. 4(a) indicates. However, a detailed description of why this happens is presented next. The empirical CDF results will be used for this purpose and they can be seen in Fig. 4(b). The important result in Fig. 4(b) is that with CB we have very good performance for users that are far from the BS since they can use all the resource blocks simultaneously and there is no interference. That is why the CDF plot for this case is progressively and smoothly increased (users are spread uniformly). With DSTC and IDSTC a bigger percentage of the UEs achieves very low throughput relative to the maximum. This happens because of two reasons. First, for nodes that are not located in the central sector, there is still some cross-BS interference even with ICIC. Second, when the two BSs transmit in the central sector they must share the OFDMA resource blocks according to ICIC an event that leads to lower spatial reuse. Note that the above two are direct results from the use of ICIC. Thus, we see that ICIC provides a very good solution when the network is not loaded to 100% of its capacity, but when the BSs have backlogged packets for transmission then there will be performance loss because of interference and reduced spatial reuse.

For the sector in the middle, performance for DSTC cannot reach a high level because when one BS transmits with the help of the relays, the other BS does not use these resource blocks leading to lower spatial reuse. Again, this is the typical result from the use of ICIC. DSTC offers lower BER which leads to throughput improvement when compared to point-to-point transmissions. With IDSTC the UEs located in the middle sector can achieve very high throughput because they can receive packets simultaneously. Thus, for nodes in the middle sector IDSTC *maximizes the maximum possible throughput that the UEs can achieve*. We see that IDSTC can



(a) Throughput/UE vs. number of UEs (b) Throughput CDF for 100 UEs

Fig. 4. Results for LTE simulation with two cells.

achieve the target objective that it is designed for, i.e. boost the performance of cell-edge users in the presence of ICI. In a system-wide simulation where all the sectors would be located at the cell edge, this result would translate to more opportunities for IDSTC to be used. This would eventually mean that the CDF of the UE throughput would be in favor of IDSTC since all the users could take advantage of it.

VI. CONCLUSIONS

In this paper we introduced the concept of interference decoding with the help of space-time coding (IDSTC). We showed that wireless signals that are interfering over the air can still reap the benefits of space-time coding without relay decoding if nodes in the wireless network cooperate. This is accomplished by applying the STC not on the symbols of interest themselves, but on the non-decodable interfered signal.

The first set of the performance results showed that significant throughput benefits can be observed over a standard distributed STC protocol. The performance benefits of our scheme were also presented for an LTE scenario. An important conclusion can be drawn from this second part of our evaluation: To improve the cell-edge performance of UEs when a low delay backhaul network communication is available we can employ CoMP for minimizing interference. However, if this is not possible an alternative is to employ UE interference cancellation (IC) at the cost of deploying low-complexity relays with simple functionality. Thus, our scheme highlights an interesting tradeoff for an operator that may either upgrade an existing BS backhaul network infrastructure to a more complex network, or deploy more low-complexity infrastructure.

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