On the Use of Space-Time Block Codes for Opportunistic Large Array Network

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***Abstract*—In this paper, deterministic space-time block codes (STBCs) are used to design orthogonal channels to transmit the information independently in a cooperative communication-based sensor network. Two topologies of two-dimensional ($2D$) opportunistic networks, the distributed grid strip and the co-located groups, having same node density are considered. Orthogonal STBCs designed for deterministic number of nodes are partially randomized with the help of indicator random vector and are used for the opportunistic multi-hop network in which the number of cooperating or decode-and-forward (DF) nodes in each hop are random. Different node geometries and the effect of increasing node number in each level are compared on the basis of one-hop success probability and network coverage at various signal-to-noise (SNR) margins. The analysis for different STBCs is made on the basis of diversity and rate it ensure at a certain required quality of service (QoS).**

I. Introduction

Cooperative communications (CC) is a transmission mode, which is recently in the lime light of researchers among the other fields of wireless communications. In a CC-based wireless system, the nodes act as multiple virtual antennas and help each other by relaying other nodes' information to achieve diversity gains, increased capacity, and reliability. This type of communication and cooperation finds its applications in both infrastructure-based wireless networks and in ad hoc wireless networks.

Opportunistic large array (OLA) is one of the types of wireless sensor cooperative networks that operates in a decode-and-forward (DF) relaying mode and propagates the message to the destination via multi-hop mechanism [1]. In an OLA network, the source broadcasts its message and all the relays in the vicinity of the source that can decode this message, relay it to the next level of nodes (or OLAs). In each hop, the relays cooperatively transmit the information towards the sink with minimal or no coordination between them, i.e., a node at a particular hop will not have any information about the number and the location of other decoding nodes of the same hop. The decision of being able to decode or not to decode is made depending upon a transmission threshold.

Many authors have studied the effect of cooperation on diversity, reliability, coverage, energy-efficiency, and rate in multi-hop cooperative networks [2]–[7]. However, very few of them have paid attention to the fact that for achieving full diversity, information needs to be transmitted by all the decoding relays through orthogonal channels even when operating on the same frequency band. Hence, there is a need to design the orthogonal channels through well known techniques; space-time code design being one of them.

Space-time block code (STBC) is a well known method, which reduces the average error probability by achieving coding and diversity gains. These codes were initially designed for co-located multiple-input multiple-output (MIMO) systems and were principled on transmitting multiple copies of the same data stream across a number of antennas. Various codes [8], [9] were designed for MIMO systems in which we have the exact information about the number of transmitting and receiving antennas. However, for ad hoc networks in general and OLAs in particular, we cannot predict the number of participating nodes that are able to decode the message and cooperatively relay the information to the unknown number of nodes in the next hop. This relaying of information using orthogonal space-time codes by the nodes that are spatially distributed is known as distributed space-time block coding (DSTBC).

Although an extensive material is available for STBCs of general MIMO systems, very few literature is available on the design of DSTBCs, and most of them do not completely satisfy the concept of distributed and randomized phenomenon. In general, the authors have assumed the assignment of STBC columns to the cooperating nodes [10]. More specifically, if an STBC is an P x M matrix, each column of the STBC matrix is assigned to each of the cooperating nodes by some central entity. These proposed DSTBCs achieve full diversity, i.e., diversity order equal to M when $N \leq M$, where N is the number of cooperating nodes. Whereas, in case of $N > M$, the loss in the diversity occurs. Some other works have considered the random assignment of space-time code columns or signature vectors on equi-probable basis [11] and by considering other stochastic randomization techniques [12]. The authors of these papers have observed the effect of increasing diversity on the probability of error. Whereas, in [13] the authors have proposed cascaded orthogonal space-time block code (COSTBC) for multi-hop network considering amplify-and-forward (AF) relaying. All of these works are performed by either considering the DF case for multiple relays between a single source destination pair, i.e., for two hop networks

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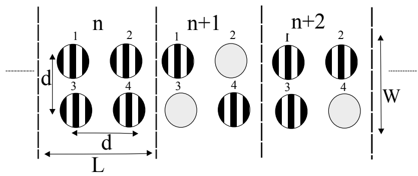

Fig. 1: 2D grid strip network layout.

only, and the AF relaying for multi-hop networks. To the best of our knowledge, none of the authors have considered the case of multi-hop cooperative network using DF relaying. Therefore, this paper mainly focuses on the design of partially randomized and distributed space-time code for DF based multi-hop cooperative communications in an OLA network.

In this paper, we consider a two-dimentional (2D) grid strip network geometry in which the number of nodes is placed uniformly along the 2D grid. Strict boundaries have been considered to group the number of nodes in each hop, which remain the same for each hop. We have also compared the performance of 2D grid strip topology with the 2D co-located groups topology. For now we have considered the orthogonal STBCs by considering the deterministic number of nodes in each hop. However, the number of DF nodes is still unknown a priori. The system is modeled by considering the flat Rayleigh fading channel with path loss effects. It has also been assumed throughout this work that the receivers have perfect channel state information (CSI).The case of out-dated CSI or no CSI is left as a future work.

The rest of the paper is organized in the following manner. In Section II, the two network models are presented along with the complete network parameters. Section III describes the transmission strategy in context of the Markov chain modeling along with the transition probability matrix for the two topologies. Results and analysis have been discussed in Section IV. Finally, Section V concludes the paper.

II. System Model

Consider an extended network of nodes that are arranged along a 2D grid, making a 2D strip cooperative network as shown in Fig. 1. Each node is a distance d apart from the adjacent nodes along each dimension. For our case, we assume that the nodes, which decode the message in a hop, i.e., the nodes represented by filled circles in Fig. 1, relay it synchronously to the nodes in the next hop using an orthogonal space-time block code. In each hop of the 2D strip network, the receiving nodes decode the message on the basis of a modulation dependent threshold. The comparison of the received signal-to-noise ratio (SNR) with the threshold is done at the output of the diversity combiner, and if the received SNR is greater than or equal to this threshold, the node will be able to decode the message and vice versa.

For the 2D strip network shown in Fig. 1, the nodes are numbered from top to bottom and then from left to right. The length of the level or hop is the number of nodes present along the horizontal direction, while the number of nodes along the vertical direction represents the width of the hop. The product of length and width gives the total number of nodes present in one hop of the 2D strip network. In general, we have, $M = L \times W$, where the total number of participating nodes in each hop is, M, L is the length, and W is the width of a hop. In case of M number of nodes in each hop, we consider to use the orthogonal STBC for M transmit antennas, i.e., STBC having M orthogonal columns. Consider a block of symbols $\boldsymbol{s} = \begin{bmatrix} s_1 & s_2 & \cdots & s_b \end{bmatrix}^T$ to be transmitted cooperatively towards the destination using M nodes of a level, where $[\cdot]^T$ denotes the transpose operation and b is the total number of symbols that makes a message block. The relay nodes in the n^{th} level use orthogonal STBC to cooperatively transmit the information symbols to the next $(n{+}1)^{th}$ level nodes on orthogonal channels. The received signals in P time slots on a k^{th} node of level $(n+1)$ can be represented as

$$\mathbf{y}_{(n+1)}^{(k)} = P_t \mathcal{G} \left(\mathbf{h}^{(k)} \circ I(n) \right) + \mathbf{z}, \quad (1)$$

where $\mathbf{y}_{(n+1)}^{(k)} \in \mathbb{C}^{P \times 1}$, i.e., $\mathbf{y}_{(n+1)}^{(k)} = \begin{bmatrix} y_1^{(k)} & y_2^{(k)} & \cdots & y_P^{(k)} \end{bmatrix}^T$ is the received signal vector at the k^{th} node of the $(n{+}1)^{th}$ hop and P_t is the transmitted power, which is assumed equal for each node. The matrix $\mathcal{G} \in \mathbb{C}^{P \times M}$ is the complex orthogonal STBC having P rows and M columns, i.e., STBC for M number of cooperating nodes, and transmission of each message block from one level to the next takes on P time slots. The vector $\mathbf{h}^{(k)} \in \mathbb{C}^{M \times 1}$, i.e., $\mathbf{h}^{(k)} = \begin{bmatrix} h_1^{(k)} & h_2^{(k)} & \cdots & h_M^{(k)} \end{bmatrix}^T$ is the channel vector and the subscript of individual elements denotes the transmitting node from the previous level. The vector $I(n) = \begin{bmatrix} \mathbb{I}_1(n) & \mathbb{I}_2(n) & \cdots & \mathbb{I}_M(n) \end{bmatrix}^T$ is the indicator or state vector for the nodes of the previous n^{th} level and its elements take on binary values indicating the DF nodes of the previous level. For instance, if the first node of the previous level has decoded the information, then $\mathbb{I}_1(n) = 1$, otherwise $\mathbb{I}_1(n) = 0$. The vector, $\mathbf{z}$, is the complex Gaussian noise vector and the mathematical operator $\circ$ denotes the Hadamard product between two vectors.

Each $h_j^{(k)}$ from the channel vector represents the fading channel from the j^{th} relay node of the n^{th} hop to the k^{th} receiving node of the $(n{+}1)^{th}$ hop. The channels between j^{th} transmitting node from the previous level to one of the node of next level are stacked to form a vector and this vector is represented in (1) as, $\mathbf{h}^{(k)}$. Each of these channel gains between a node pair also takes into account the path loss between them. Therefore, we define $h_j^{(k)}$ as, $h_j^{(k)} = \frac{\alpha_{jk}}{d_{jk}^{\beta}}$, here α_{jk} is the complex Gaussian random variable with zero mean and unit variance representing Rayleigh fading, d_{jk} is the Euclidian distance between the two nodes, and β is the path loss exponent that can be in range of 2-4. The channel is assumed static during the transmission of one block. Therefore, $h_j^{(k)}$ remains constant for the transition of one message block. At each k^{th} receiver, decoding takes place by using the decoding matrix as given in (2), i.e.,

$$\tilde{\mathbf{s}}^{(k)} = \mathcal{H} \mathbf{y}_{(n+1)}^{(k)}. \quad (2)$$

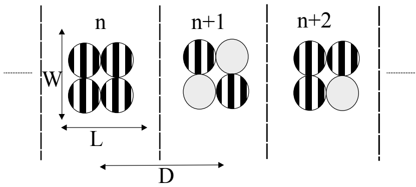

Fig. 2: 2D Co-located groups topology.

In (2), $\mathcal{H}= \mathcal{G}^{H}$ is the decoding matrix and is assumed to be known at receiver and $[\cdot]^{H}$ represents the Hermitian operator. The above equation shows the maximal ratio combining (MRC) at the k^{th} node, Where, $\tilde{\mathrm{s}}^{(k)}$ is the received message block. After substitution of respective matrices, the above expression can be represented as

$$\tilde{\mathbf{s}}^{(k)} = \sum_{j \in \mathbb{N}_n} |h_j^{(k)}|^2 \mathbf{s}. \tag{3}$$

This shows that the whole block of symbols will be received with a gain of $|\mathbb{N}_n|$, where $|\mathbb{N}_n|$ is the cardinality of set $\mathbb{N}_n$, which consists of the indices of the nodes that decoded the signal perfectly at the n^{th} hop. Similarly, the message signal in the form of block will be received at each node of the $(n+1)^{th}$ level. The decision of the node to decode the message perfectly, as mentioned before, depends upon the transmission threshold, τ, i.e., if the received power at the k^{th} node is greater than or equal to τ, the node will correctly decode the message block. Hence the expression for the received power from (3) can be given as

$$Pr_{(n+1)}^{(k)} = P_t \sum_{j \in \mathbb{N}_n} |h_j^{(k)}|^2. \tag{4}$$

From (4), it can be observed that the received power at a receiving node depends on the transmitted power, distance between the adjacent nodes, path loss exponent, and Rayleigh fading channel gain of the nodes that decoded the message correctly in the previous n^{th} hop. This channel gain from the nodes that have correctly decoded, depends upon the Euclidean distance between the nodes. It has been assumed that all the nodes that correctly decode the message in a hop or level, relay the symbols of a message block to the nodes in the next level at the same time, i.e., there is perfect transmit synchronization between the nodes along with perfect timing recovery at each receiver [2].

A. 2D Co-Located Groups Topology

In this subsection, we consider a different topology in which the nodes in each level are placed closely in a co-located fashion to form a group as shown in Fig. 2. The only difference between the distributed 2D grid strip topology and the 2D co-located topology is the distance between the adjacent nodes, which is quite negligible for the co-located group case. Hence, this negligible spacing between the nodes can therefore be ignored. The only distance that can be taken into consideration is the inter-group distance, and that can be represented as $D \approx Ld$, where L is the number of co-located nodes present along the length in each group and d is the inter node distance in the distributed topology. This means that all nodes of one group are approximately D distance apart from the nodes of the group in the next level. All other assumptions, e.g. synchronization and timing recovery will also remain valid for this model. Similarly, the co-located nodes from each group that decodes the message use orthogonal STBCs to cooperatively transmit the message to the group of nodes in the next level and therefore (1) remains valid for this case also. The only difference as mentioned before is the inter-group distance, D, instead of inter-node distance, d, which in turn effects the path loss and so the channel gain between any two transmitter receiver node pair. i.e., $h_j^{(k)}$ can now be expressed for co-located topology as, $h_j^{(k)} = \frac{\alpha_{jk}}{D^{\beta}}$.

III. Transmission Modeling

As it can be deduced from (1) that the decision of the nodes of the present level to decode the message block, only depends upon the nodes that have decoded the message in the previous hop or level only. Therefore, this network behavior can be modeled using Markov chain, where each node in a hop can either be in state 1 or 0 if it has perfectly decoded or not, respectively. Hence, the state of each j^{th} node of n^{th} level or time instant, can be represented by a binary indicator random variable as used in (1), i.e, $\mathbb{I}_j(n)$.

Therefore, the state of the network at any time instant n can be represented as M-bit binary word $\tilde{I}(n)$. This indicator RV collectively represents the state of each node of present hop as

$$\tilde{I}\left(n\right) = \begin{bmatrix} \mathbb{I}_1\left(n\right) & \mathbb{I}_{(W+1)}\left(n\right) \cdots \mathbb{I}_{(L-1)(W+1)}\left(n\right) \\ \mathbb{I}_2\left(n\right) & . & & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ \mathbb{I}_W\left(n\right) & \mathbb{I}_{2W}\left(n\right) & \ldots & \mathbb{I}_M\left(n\right) \end{bmatrix}. \tag{5}$$

For example, from Fig. 1, at level $(n+1)$, $\mathbb{I}_1(n+1)$=1, $\mathbb{I}_2(n+1)$=0, $\mathbb{I}_3(n+1)$=0, and $\mathbb{I}_4(n+1)$=1. Therefore , $\tilde{I}\left(n+1\right) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$. In order to convert the above state representation into linear or M-tuples form, i.e., $I = \begin{bmatrix} \mathbb{I}_1 & \mathbb{I}_2 & \cdots & \mathbb{I}_M \end{bmatrix}^T$, vec vector operation is applied to (5) as $I(n) = \left\{vec\left[\tilde{I}\left(n\right)\right]\right\}^T$. Hence, state of the network in Fig. 1 at time instant $n+1$ can be expressed as $I(n+1) = [1001]^T$. At this point 2D Markov chain has taken the form of 1D representation. The state space will have 2^M-1 transient states in addition to an absorbing state that eventually terminates the transmission. An absorbing state is the state in which all the nodes of a hop fail to decode the message block, thus terminating the message propagation.

A. Transition Probability Matrix

The Markov chain, $I(n)$ can be defined completely by union of two sets, the transient state space X, i.e., $X = \{1, 2, ..., 2^{M-1}\}$ and $\{0\}$ the absorbing state. Each element of the set X will take on a binary word representation form, which can be termed as indicator or state vector. The other set $\{0\}$ is the set of all zeros and there is always a non-zero probability of transiting to this state which increases asymptotically as, $\lim_{n \to \infty} \mathbb{P}\left\{I\left(n\right) = 0\right\} \nearrow 1$.

The concept of absorption with non-zero positive probability results in the quasi-stationary distribution for the given Markov chain [2]. An irreducible and right sub-stochastic transition probability matrix $\mathbf{P}$ having dimensions $\left(2^M-1\right)\times\left(2^M-1\right)$ is then formed by removing the transitions to or from the absorbing state. The Perron-Frobenius theorem is then invoked on $\mathbf{P}$ to get the maximum eigenvalue and the left eigenvector.

Each entry of the transition probability matrix represents the probability of being transiting to one of each possible transient states. Whereas, each state tuple depends upon the binary state of each node at any specific level or time instant say n, i.e., the decoding probability of k^{th} node in n^{th} level can be given as $\mathbb{P}\left\{\mathbb{I}^{(k)}(n)=1\right\}=\mathbb{P}\left\{\Pr^{(k)}(n)\geq\tau\right\}$. Whereas, $1-\mathbb{P}\left\{\Pr^{(k)}(n)\geq\tau\right\}$ or $\mathbb{I}=0$ is the probability of being in outage, and $\mathbb{P}\{Pr^{(k)}(n)\geq\tau\}$ can be written as $\mathbb{P}\{Pr^{(k)}(n)\geq\tau\}=\int\limits_0^\infty f_{pr^{(k)}}(y)\,dy$. In this expression $f_{pr^{(k)}}(y)$ is the probability density function (PDF) of received power at node k. The distribution of received power Pr depends upon the topology in which the nodes are arranged, i.e, the PDF of received power at a node may follow different distributions in case of distributed and co-located topologies.

1) Transition Probability Matrix for 2D Grid Strip Network Topology: For distributed $2D$ grid strip topology, the received power at the k^{th} node is the sum of the the exponentially distributed powers from the previous level with distinct parameter $\lambda_j^{(k)}$. These powers are exponentially distributed because of the square of each channel gain as in (3), and the sum of these $|\mathbb{N}_n|$ exponentially distributed powers results in a hypoexponential distribution [2], that can be given as, $f_{pr}^{(k)}(y)=\sum\limits_{j=1}^{\mathbb{N}_n}C_j^{(k)}\lambda_j^{(k)}\exp(-\lambda_j^{(k)}y)$. Hence, one-step probability of transiting from state a to state b will be,

$$\mathbb{P}_{ab}=\prod_{k\in\mathbb{N}_{n+1}^{(b)}}\left\{\sum_{j\in\mathbb{N}_n^{(a)}}C_j^{(k)}exp(-\lambda_j^{(k)}\tau)\right\}$$
$$\prod_{k\in\overline{\mathbb{N}}_{n+1}^{(b)}}\left\{1-\sum_{j\in\mathbb{N}_n^{(a)}}C_j^{(k)}exp(-\lambda_j^{(k)}\tau)\right\}. \quad (6)$$

where $\sum\limits_{j\in\mathbb{N}_n^{(a)}}C_j^{(k)}exp(-\lambda_m^{(k)}\tau)$ is the probability of success at node k, $\lambda_j^{(k)}=\frac{(d_{jk})^\beta\sigma_j^2}{Pt}$, and $C_j^{(k)}=\prod_{\varsigma\neq j}\frac{\lambda_\varsigma^{(k)}}{\lambda_\varsigma^{(k)}-\lambda_j^{(k)}}$. The sets $\mathbb{N}_{n+1}^{(b)}$ and $\overline{\mathbb{N}}_{n+1}^{(b)}$ represents the indices of DF nodes and unsuccessful nodes (nodes having $\mathbb{I}^{(k)}(n)=0$) of state b at the $(n+1)^{th}$ level, respectively.

2) Transition Probability Matrix for 2D Co-Located Groups Topology: Similarly in this case, the received power at each node in group again will be the sum of exponentially distributed powers from the DF nodes of the previous nodes but with same parameter $\tilde{\lambda}=\frac{D^\beta\sigma_k^2}{Pt}$. As the inter-node distance is almost negligible and the nodes in a level are co-located to form a group therefore, they will have the same path losses, and distribution parameter to the nodes in the next level. Hence, the exponentials having same parameter will result in a Gamma distribution for the received power [3], and the received power PDF will be,

$$f_{pr}^{(k)}(y)=\frac{1}{(|\mathbb{N}_n|-1)!}\tilde{\lambda}^{|\mathbb{N}_n|}y^{(|\mathbb{N}_n|-1)}exp(-\tilde{\lambda}y). \quad (7)$$

Hence, the one step success probability at k^{th} node of the next level is, $\exp(-\tilde{\lambda}\tau)\sum\limits_{j=0}^{|\mathbb{N}_n(a)|-1}\frac{(\tilde{\lambda}\tau)}{j!}$. The one step success probability in (6) will be replaced by this expression for the co-located groups case, and the final expression then comes out to be,

$$\mathbb{P}_{ab}=\prod_{k\in\mathbb{N}_{n+1}^{(b)}}\left\{\exp(-\tilde{\lambda}\tau)\sum_{j=0}^{\left|\mathbb{N}_n^{(a)}\right|-1}\frac{\left(\tilde{\lambda}\tau\right)}{j!}\right\}$$
$$\prod_{k\in\overline{\mathbb{N}}_{n+1}^{(b)}}\left\{1-\exp(-\tilde{\lambda}\tau)\sum_{j=0}^{\left|\mathbb{N}_n^{(a)}\right|-1}\frac{\left(\tilde{\lambda}\tau\right)}{j!}\right\}. \quad (8)$$

IV. Results and Analysis

In this section, we present the results that demonstrate the system performance by the implementation of different STBCs for different number of nodes, M, in each level, followed by some comparisons and analysis. We first present the relative comparison of one-hop success probability obtained analytically through Perron-Frobenius eigenvalue, ρ, of the transition matrix in (6) for $M=6$, but with the variation in the values of L and W for distributed case. This one-step success probability, ρ_{dis}, for distributed case is shown as function of SNR margin, γ, where γ is the normalized SNR with respect to τ, which can be defined as $\gamma=\frac{P_t}{\sigma^2\tau}$. The values for some other system parameters are $d=1$, $\beta=2$ or 3, and $P_t=1W$.

Fig. 3 demonstrates the behavior of one-hop success probability, ρ_{dis}, for the distributed network topology for $\beta=2$. Hop size M is kept constant for this case, i.e., $M=6$, and different combinations of L and W are considered. To carry out this comparison, we used orthogonal STBC for six antennas given in [9] and it takes on 30 time slots to transmit a block of 18 symbols cooperatively from one hop to the next. Generally, it can be observed that for all possible combinations of L and W, one-hop success probability increases with the increase in γ, where increase in γ results in decrease of τ, making more nodes to correctly decode the information. However, for a specific value of γ, the first two 2D distributed cases seem to achieve better ρ_{dis} as compared to 1D distributed case, i.e., $L=6$ and $W=1$. For the $2D$ case, the one combination having greater number of nodes across the width, ($L=2$, $W=3$) provides better ρ_{dis} as compared to the other combination in which there are more nodes across the length of a hop ($L=3$, $W=2$). The reason behind this behaviour is the Euclidean distances between the nodes of two hops that are least for the first case, on average, as compared to the other two cases. This distance in turn effects the path loss and hence the performance gain.

Fig. 4 represents the difference between the one-hop success probability, ρ_{dis}, obtained from simulations and from analytical model. The value of parameter M used in Fig. 4 are $M=4$

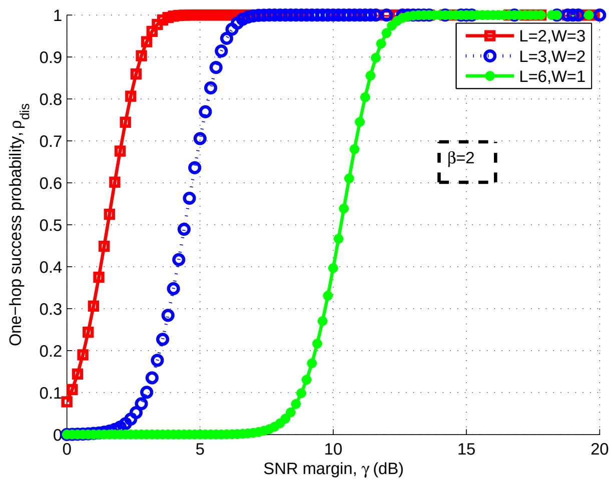

Fig. 3: One-hop success probability for 2D distributed grid network.

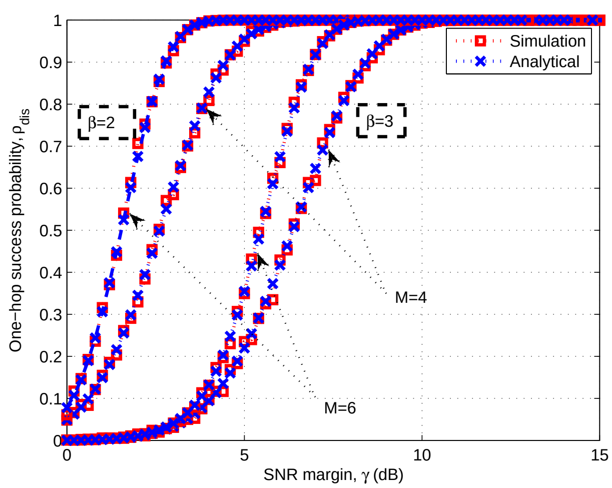

Fig. 4: Comparison of ρ_{dis} obtained through simulations and analytical model.

($L = 2$, $W = 2$) and $M = 6$ ($L = 3$, $W = 2$) for different values of γ. The plot shows that the analysis and simulation results match closely for different cases. In simulations, the one-hop success indicates that at least one node decodes the message correctly. The forthcoming results are all based on theocratical models.

In Fig. 5, the network performance is analyzed by evaluating the coverage in terms of maximum number of hops traversed or the maximum number of nodes along the length of network that receives the information with a given quality of service (QoS) constraint, η. In our case, we obtain the maximum coverage when we require our system to operate at above 90% success probability for all hops, i.e., $\eta \geq 0.9$. Now if ρ_{dis} is the one-hop success probability then the success probability until ℓ^{th} hop will be ρ_{dis}^{ℓ}. Therefore, to transmit the information block to ℓ^{th} hop with 90% success probability, we require, $\rho_{dis}^{\ell} \geq \eta$. From here it can be deduced that the maximum number of hops that can be traversed by the information blocks on average, with the required success probability are $\ell \leq \frac{ln\eta}{ln\rho_{dis}}$. This maximum hop value, ℓ when multiplied with

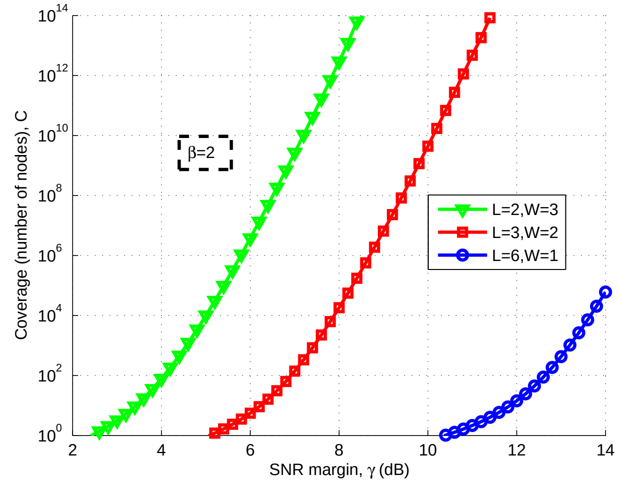

Fig. 5: SNR margin vs. maximum coverage for $M = 6$.

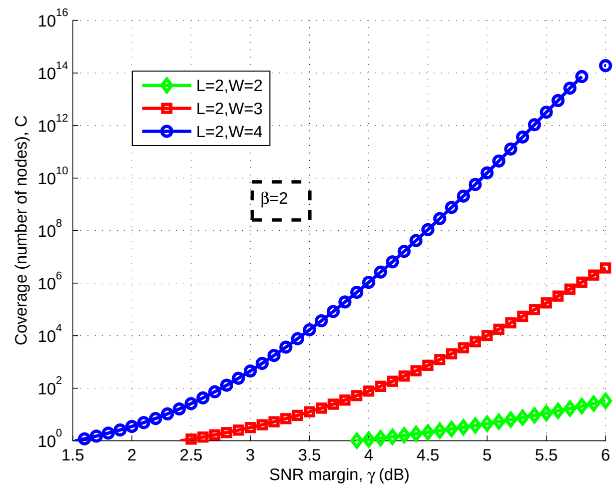

Fig. 6: SNR margin vs. maximum coverage for various values of M.

the L results in the average number of nodes, $\mathcal{C}$, that receives the information. The plot is generated for the three mentioned geometries for $M = 6$, and it can be seen from Fig. 5 that the combination $L = 2$ and $W = 3$ provides the highest coverage value at each possible SNR margin as compared to the other two combinations of L and W.

Fig. 6 shows the general effect of increasing hop size M on the coverage for various values of W, and for a fixed L. This figure shows that while considering a certain geometry of nodes, the increase in M results in higher coverage for the same required SNR margin.

The overall comparison of the distributed 2D strip network topology is being summarized in Table I, where P is the number of time slots that an STBC takes on, T_d is the overall delay, and R is the rate. The table quantifies the effect on various parameters for a fixed coverage range, i.e., $\mathcal{C} = 24$, where nodes can be arranged in different geometries. For the case in which $M = 6$, $L = 2$, and $W = 3$, we use an STBC of 3/5 rate provided in [9] that transmits a block of 18 symbols from one hop to the next in 30 time slots. Therefore, the

TABLE I: Comparison for optimal STBC and node geometry

M	L	W	$STBC$	Coverage		P	T_d	R	γ
				$\mathcal{C}$	ℓ		$P \times \ell$		(dB)
4	4	1	3/4 rate	24	6	4	24P	3sym/24P	11.27
4	2	2	3/4 rate	24	12	4	48P	3sym/48P	5.85
6	6	1	3/5 rate	24	4	30	120P	18sym/120P	12.19
6	3	2	3/5 rate	24	8	30	240P	18sym/240P	6.50
6	2	3	3/5 rate	24	12	30	360P	18sym/360P	3.67
8	8	1	1/2 rate	24	3	8	24P	4sym/24P	13.04
8	4	2	1/2 rate	24	6	8	48P	4sym/48P	7.26
8	2	4	1/2 rate	24	12	8	96P	4sym/96P	2.45

transmission of a message block to the 24^{th} node or 12^{th} hop, takes on 360 time slots. Thus, $3/5$ rate STBC transmits the message blocks to 24^{th} node with a maximum rate of 18 symbols /$360P$. From Table I, it can be inferred that if the horizontal stretch of a hop contains more nodes, then the information is transmitted towards the far away nodes with lower delay and at high SNR margin. Whereas, if we increase the number of nodes along the width and keep L constant then with the increase in W, diversity increases and information transverses towards its destination with higher delay but at a lower SNR margin. This shows that there is a tradeoff between delay and required SNR margin. Hence, the selection of an optimal STBC and node geometry mainly depends upon the type of application or scenario in which we want to operate, i.e., if the application is more energy-constraint then we select the one that requires lower SNR margin, e.g. half rate STBC with $L = 2$ and $W = 4$, otherwise, for delay sensitive applications, linear or $2D$ geometry having larger L should be used.

In the end, we make a comparison between two topologies discussed before, the distributed and co-located groups topology. The eigenvalues for distributed and co-located groups topology gives the one-hop success probability and are denoted as ρ_{dis} and ρ_{col}, respectively. In Fig. 7, the difference between the two success probabilities, $\rho_{dis} - \rho_{col}$ is plotted vs. the SNR margins for path loss exponent of 2, and that results in a Gaussian-shaped curve. These curves are generated for three different topologies keeping M equal to 6. Fig. 7 shows that the maximum difference increases if we arrange more nodes along vertical direction, i.e., larger W in distributed case. These positive difference curve shows that co-located case performs better than distributed one at lower SNR margins. Although, the plots show that the co-located topology gives better success probability than distributed one, however, in some sensing scenarios co-located geometry does not provide accurate or updated information about the points that are spatially distributed. Hence, for these scenarios the nodes need to be arranged in a distributed manner.

V. Conclusion

We have introduced a way to construct orthogonal channels by using STBCs for $2D$ opportunistic large array sensor networks. Deterministic STBCs are made random with the help of indicator or state vector, which are then used by the random opportunistic nodes at each level. Markov chain and Perron-Frobenius eigenvalue decomposition are used to completely model the network state and the transmission strategy. The performance of each parameter is then analyzed

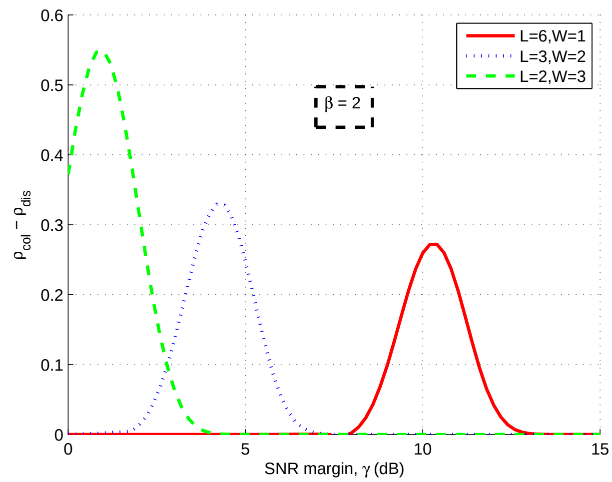

Fig. 7: One-hop success probability differences between co-located and distributed topologies.

at different SNR margins. In future, we aim to design a fully randomized STBC for OLA network, considering randomized node positions and for different fading environments.

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