Journal de Ciencia e Ingeniería, Vol. 7, No. 1, Agosto de 2015, pp. 10-18
**Investigación - Telecomunicaciones**

# Peer-to-peer Link Implementation Analysis in MIMO Ad Hoc Network

## Análisis de Implementacion de Enlace Punto a Punto en red MIMO tipo ad hoc

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Recibido: 03/03/2015; revisado: 06/05/2015; aceptado: 24/07/2015

**A. Lambertt Lobaina, V. Zaharov:** Peer-to-peer Link Implementation Analysis in MIMO Ad Hoc Network. Jou.Cie.Ing. **7** (1): 10-18, 2015. ISSN 2145-2628.

**Abstract**

MIMO ad hoc wireless network peer-to-peer link implementations for different MIMO transmission-receiving schemes are discussed. The following MIMO links are considered, namely, blind transmission with space-time coding (BTSTC) in absence of channel state information on the transmitter side (CSIT), spatial multiplexing with the Butler matrix (SDMA) without CSIT, spatial multiplexing with singular value decomposition (SVD) of a channel matrix (SMSVD) in the presence of CSIT, and spatial multiplexing adaptive beamforming (SMAB) with CSIT. Comparative analysis of mentioned implementations involving signal-to-interference-plus-noise-ratio (SINR), symbol-error-rate (SER), computational complexity, and feedback requesting is done. Some recommendations for practical applications of mentioned implementations according to introduced criteria are given.

***Keywords*:** MIMO ad hoc networks, array signal processing, channel state information, MIMO capacity, multiuser communications, spatial multiplexing, Butler matrix.

**Resumen**

Se discuten implementaciones de enlaces de redes inalámbricas ad hoc ”par-a-par” para diferentes esquemas transmisión-recepción MIMO. Los siguientes enlaces MIMO son considerados particularmente, transmisión sin salida con codificación espacio-tiempo (BTSTC) en ausencia de canal información de estado en el lado transmisor (CSIT), matriz de multiplexacion espacial con matriz ”Butler” (SDMA) y sin CSIT, multiplexión espacial con descomposición de valor singular (SVD) de una matriz de canal (SMSVD) en presencia de CSIT, adaptable y haces de multiplexión espacial (SMAB) con CSIT. Análisis comparativo de las implementaciones de señal-a-interferencia-mas-ruido (SINR), tasa-error-símbolo (SER), complejidad computacional, y la información de realimentación que solicita. Algunas recomendaciones para las aplicaciones prácticas de las implementaciones de acuerdo para aplicar los criterios.

***Palabras Clave*:** Redes MIMO adhoc, procesamiento de señal de la red de antenas, la información de estado del canal, la capacidad MIMO, comunicaciones multiusuario, multiplexado espacial, matriz Butler.

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## 1. Introduction

With emerging on the market 4G wireless networks the ad hoc networks are getting integral part of the 4G information infrastructure [1, 2]. It is basically peer-to-peer networks of hosts (more probably mobile) that have neither fixed communication infrastructure nor any master base stations. The nodes, as a rule, use distributed medium access protocols such as IEEE 802.11 to reserve local access to the wireless medium [3].

To improve the transmission efficiency of peer-to-peer networks without need of neither extra bandwidth nor consuming energy the transmission technique that use multiple-input-multiple-output (MIMO) was extended to ad hoc network applications [4,5]. Using multiple antennas at two sides of peer-to-peer communication links helps significantly improve the transmission efficiency due to exploring spatial selectivity, establishing the orthogonal virtual space channels making effective partition of the total time-frequency space network resources [6,7]. As a result, application of MIMO technology to ad hoc networks allows to achieve much higher spectral efficiencies than traditional communication systems, providing high data throughput, improved system performance, and so on.

As a premium options, MIMO ad hoc network that contains multi-antenna nodes helps to establish the access to all active users by allowing simultaneous transmissions in a way that leaves no idle channels. Such facilities are rather difficult to deploy in ad hoc network with omnidirectional antennas nodes due to the lack of a central node. In addition, by simultaneous transmissions MIMO ad hoc transmission system can also exploit the multiuser diversity, propagation channel diversity, potentially improving the overall ad hoc network performance [4, 8].

On the other hand, allowing simultaneous transmissions in MIMO ad hoc network any two wireless peer-to-peer links would cause excessive interference on each other. For traditional ad hoc networks with omnidirectional antennae it requires assigning of different time or frequency channels for each peer-to-peer link. However, for ad hoc MIMO links the spatial filtering capabilities help to operate in the same frequency or time slot for both links, but stream control is needed to avoid data collision [9,10]. Stream control is possible only if channel state information at the transmitter side (CSIT) is available, i.e., transmitter has channel knowledge [11]. Hence, the feedback loop capacities of associated interfering MIMO links are required.

Therefore, the main problem of ad hoc network deployment is the choice of appropriate MIMO link implementation, and the solution of this problem in general is a finding of the reasonable trade-off between implementation complexity and acceptable performance. There are a lot of implementation schemes of MIMO ad hoc network proposed in the literature [2, 4, 12–14], which are differ by operational performance, implementation complexity, feedback capacities, and so on. As a rule, the main performance criterion of peer to peer link quality are symbol error rate (SER), or related to it signal-to-interference-plus-noise-ratio (SINR). Nevertheless, the performance of MIMO ad-hoc link very dependable on their implementation, i.e., transmission scheme, availability of the channel state information, diversity, multiplexing technique and so on. Despite the bunch of MIMO link implementations has been described in the literature quite in details, the comparative analysis of various implementations from point of view of performance, computational complexities and feedback loop capacities is not done yet. This paper goal is to bring the contribution into this analysis.

To achieve the objective, firstly, we obtained and analyzed SINR of MIMO ad hoc wireless link for the following more frequently used practical implementations: a) Blind transmission using space-time coding (BTSTC); this scheme does not require CSIT, but extracts transmit diversity. b) Spatial multiplexing with transmission of multiple independent data streams without any CSIT using the Butler matrix; this transmission is known in the literature as Space Division Multiple Access (SDMA) [14]. c) Spatial multiplexing with singular value decomposition of a channel matrix (SMSVD) in the presence of CSIT. It extracts both diversity and array gains. d) Spatial multiplexing with CSIT and adaptive beamforming that uses CSIT to suppress deeply the interferer signals. Secondly, the performance, computational complexity and feedback capacities for each of the mentioned implementations are found and, finally, comparative analysis is done.

## 2. MIMO Ad Hoc Wireless Channel and Signal Models

Let us consider ad hoc network with simultaneously communicating transmitter-receiver node pairs. Both transmitter and receiver are equipped with the uniform linear array (ULA) of $M_t$ and $M_r$ antennas, respectively, as Fig. 2 shows. All MIMO ad hoc nodes communicate in the Rayleigh fading propagation environment with rich scattering, and each transceiver pair attempts to suppress interferer signals by using well-known ability of multiple antennas [7]. We assume also that all nodes have identical power constraint. We introduce the channel matrix model for arbitrary transmitter-receiver pair as

$$\mathbf{H} = \mathbf{R_r}^{1/2}\mathbf{H}_{\mathcal{N}}\mathbf{R}_t^{1/2}, \quad (1)$$

where $\mathbf{H}_{\mathcal{N}} \in \mathbb{C}^{M_r \times M_t}$ is the i.i.d. complex values $\mathcal{CN}(0,1)$, which are the collection of all channel propagation coefficients, $\mathbf{R}_r$ and $\mathbf{R}_t$ are receiver and transmitter correlation matrices, respectively [15]. Furthermore, we ignore the large scale propagation attenuation of the received signal, assuming that $\sum_{j=1}^{M_t} E\{|h_{ij}|^2\} = M_t$, where $i = 1, 2, \ldots, M_r$, $E\{\cdot\}$ is the expectation operator, and $h_{ij}$ are elements of the matrix $\mathbf{H}$. This implies that each of the receiver antenna receives a power, which is equal to the total transmitted power $P$. Additionally, we assume that matrix $\mathbf{H}$ has a full rank, that is, $\texttt{rank}\{\mathbf{H}\} = \min\{M_t, M_r\}$.

In MIMO link the channel matrix can be easy estimated at the receiver side by sounding the channel with training signal, hence, we suppose that the channel state information (CSI) is available on the receiver side. To be available on the transmitter side CSI should be retransmitted through the feedback channel, which requires some additional bandwidth resources. As a result, the singular value decomposition of the propagation channel matrix, $\mathbf{H} = \mathbf{U}\Sigma\mathbf{V}^\dagger$, can be computed [16], where $\mathbf{U}$ and $\mathbf{V}$ are the matrices with orthonormal properties, $\Sigma = diag\{\sigma_1, \sigma_2, \ldots, \sigma_r\}$ is a diagonal matrix with the singular values entries, $r$ is the rank of the matrix $\mathbf{H}$, and $\dagger$ is a conjugate and transpose symbol.

We assume that transmitted signal $\mathbf{s} \in \mathbb{C}^{M_t \times 1}$ is a column vector with i.i.d. standard Gaussian entries $s_i,\ i = 1, 2, \ldots, M_t$, whose covariance matrix is

$$\mathbf{R}_{ss} = E\{\mathbf{ss}^\dagger\} = \mathbf{I}_{M_t}, \quad (2)$$

where $\mathbf{I}_{M_t}$ is the identity matrix of the size $M_t$.

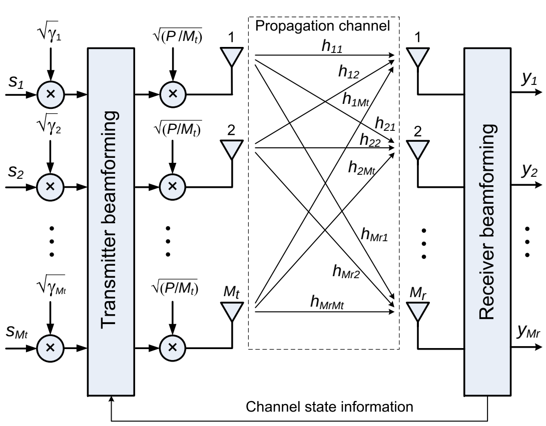


Fig. 1. Transmitter-receiver node pair in MIMO ad hoc network.

Using beamforming approach, as Fig. 1 shows, receiver node input-output signals relationship can be written as

$$\mathbf{y} = \sqrt{P}\mathbf{W}_r^\dagger\mathbf{H}\mathbf{W}_t\Upsilon^{\frac{1}{2}}\mathbf{s} + \mathbf{W}_r^\dagger\mathbf{n}, \quad (3)$$

where $\mathbf{W}_t \in \mathbb{C}^{M_t \times M_t}$ and $\mathbf{W}_r \in \mathbb{C}^{M_r \times M_r}$ are transmitter and receiver beamformer matrixes, which consist the column-vectors $\mathbf{w}_{t(i)}$ and $\mathbf{w}_{r(j)}$, respectively, with the unit 2-norms $\|\mathbf{w}_{t(i)}\|_2^2 = \|\mathbf{w}_{r(j)}\|_2^2 = 1$; $\Upsilon = diag\{\gamma_1, \gamma_2, \ldots, \gamma_{M_t}\}$ is a diagonal matrix with the elements equal to sub-channel power allocation factors, which in presence of the channel state information on the transmitter side (CSIT) help to feed each transmitting antenna to achieve the maximum data throughput [9, 17], $\mathbf{n} \in \mathbb{C}^{M_r \times 1}$ is a AWGN vector with the entries $\mathcal{CN}(0,1)$ and the power $\mathcal{N}$, and $\mathbf{y} \in \mathbb{C}^{M_r \times 1}$ is an output vector.

The transmitter and receiver beamformer vectors, $\mathbf{w}_{t(i)}$ and $\mathbf{w}_{r(j)}$, are chosen to optimize some cost function. For example, in the case of a simple scenario, where only single peer to peer link is active meaning absence of the interferer nodes, the cost function could be the signal-to-noise-ratio (SNR) for each virtual subchannel realization. As follows from (3) the SNR in output of *i*th virtual sub-channel of a receive node yields

$$SNR_i = \frac{P\gamma_i|\mathbf{w}_{r(i)}^\dagger\mathbf{H}\mathbf{w}_{t(j)}|^2}{\|\mathbf{w}_{r(i)}\|_2^2\,\mathcal{N}}, \quad (4)$$

where the maximum signal power in the output of the *i*th virtual sub-channel can be found by solving the optimization problem

$$P_{s_i} = \arg\max_{\forall \mathbf{w}_{r(i)}, i=1,2,\ldots,M_r} \mathbf{w}_{r(i)}^\dagger\mathbf{H}\mathbf{w}_{t(j)}, \quad (5)$$

and (5) succeeds maximum when $i = j$.

However, because of real ad hoc MIMO communication link, as a rule, operates in the presence of interferer signals, which are coming from other active in the same time nodes, throughout the paper we will use another cost function, that is, signal-to-interference-plus-noise-ratio (SINR), which will be introduced above for each particular implementations of MIMO links.

## 3. MIMO Performance in the absence of CSIT

### 3.1. *MIMO blind transmission mode*

In the absence of CSIT, the blind transmission schemes is used, i.e., the transmitter and receiver beamforming matrixes, which are introduced in (3), are $\mathbf{I}_{M_t}$

and $\mathbf{I}_{M_r}$, respectively. Depending on the interferer-noise-ratio (INR) the transmitter can operate in two modes. Fist, the weak interference mode when the transmitter should put equal power on all antennas providing the optimal interference free transmission. Second, a singular mode (strong interference mode) when the transmitter puts all its power on a single antennas or transmitting identical information through all antennas [4].

We refer to the receiving node that receives the signal of interest $\mathbf{s}^{(d)}$ from desired node, as well as $K$ interferer signals $\mathbf{s}^{(k)},\ k = 1, 2, \ldots, K$, which transmitted by interferer nodes. The corresponding channel propagation matrixes related to the desired node are $\{\mathbf{H}^{(d)}, \mathbf{H}^{(1)}, \ldots, \mathbf{H}^{(K)}\}$. The described scenario depicted in Fig.2.

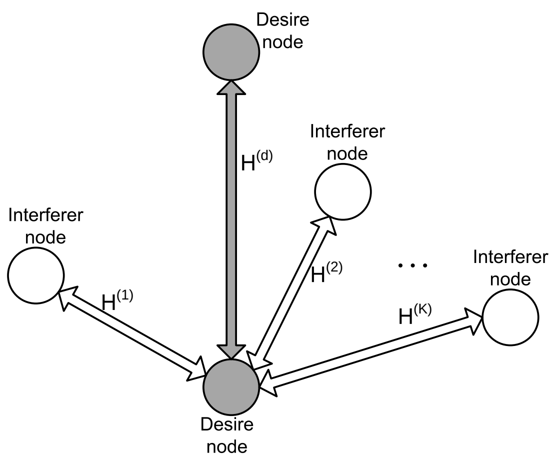


Fig. 2. MIMO ad hoc communication scenario.

Therefore, the receiving vector in output of desired node is

$$\mathbf{y} = \sqrt{P^{(d)}}\mathbf{I}_{M_r}\mathbf{H}^{(d)}\mathbf{I}_{M_t}\Upsilon^{\frac{1}{2}}\mathbf{s}_{STC}^{(d)} + \sum_{k=1}^{K}\sqrt{P^{(k)}}\mathbf{I}_{M_r}\mathbf{H}^{(k)}\mathbf{I}_{M_t}\mathbf{s}_{STC}^{(k)} + \mathbf{I}_{M_r}\mathbf{n}, \quad (6)$$

where $\mathbf{s}_{STC}^{(d)}$ is an input data vector that permutated to space-time coding (STC) matrix [15, 18], and $\Upsilon$ is a matrix that redistributed the power depending on weak or strong interferer mode transmission.

The resulting SINR for the *i*th virtual sub-channel yields

$$SINR_i = \frac{P^{(d)}\alpha^{(d)}\|\mathbf{H}^{(d)}\|_2^2}{\sum_{k=1}^{K} P^{(k)}\alpha^{(k)}\|\mathbf{H}^{(k)}\|_2^2 + \mathcal{N}}. \quad (7)$$

where $\alpha^{(d)}$ and $\alpha^{(k)}$ corresponding STC gains.

As (7) shows, to avoid serious degradation of the SINR in output of the desired receiver in the MIMO blind transmission mode, the transmitting interferer nodes with the high level of $P^{(k)}$ are preferably remain idle, especially when the norm of matrix $|\mathbf{H}^{(k)}\|_2^2$ is high, meaning the favorable propagation condition for $k$th interferer node.

MIMO blind transmission mode can be considered as the simplest MIMO implementation. It is not require the CSIT, hence, no feedback transmission is needed. The computational work, according to (6) is $M_t$ semi-complex operations (multiplications and summations).

### 3.2. *MIMO with the Butler Matrix Beamforming*

As has been shown in previous subsection the absence of CSIT does not allow suppress the interferers quite deeply and the transmitter either transmits the signal with uniform distributed power or puts all power on a single antenna. However, despite the absence of CSIT the performance of ad hoc network can be improved just replacing the matrixes $\mathbf{I}_{M_t}$ and $\mathbf{I}_{M_r}$ by new transmitter and receiver matrixes, which are the Butler beamforming matrixes, i.e, $\mathbf{W}_t = \mathbf{A}_t$, $\mathbf{W}_r = \mathbf{A}_r$. Actually they are the discrete Fourier transform (DFT) matrices [19], where the columns $\mathbf{a}_{t(i)}$ and $\mathbf{a}_{r(j)}$ represents *i*th transmitter and *j*th receiver virtual space signatures [20], respectively, meaning $\mathbf{w}_{t(i)} = \mathbf{a}_{t(i)}$, $\mathbf{w}_{r(j)} = \mathbf{a}_{r(j)}$, and the vectors $\mathbf{a}_{t(i)}$ and $\mathbf{a}_{r(j)}$ define as

$$\mathbf{a}_{t(i)} = \left[1, e^{-j\pi\theta_{t(i)}}, \ldots, e^{-j(N_t-1)\pi\theta_{t(i)}}\right]^T, \quad (8)$$
$$\mathbf{a}_{r(j)} = \left[1, e^{-j\pi\theta_{r(j)}}, \ldots, e^{-j(N_t-1)\pi\theta_{r(j)}}\right]^T,$$

where $\theta_{t(i)} = (d_t/\lambda)\sin\phi_{t(i)}$ and $\theta_{r(j)} = (d_r/\lambda)\sin\phi_{r(j)}$ are physical *i*th transmitting and *j*th receiving space angles, respectively, related to the array horizontal axis, $d_t$ and $d_r$ are corresponding transmitter and receiver array antenna distance, $\lambda$ is a carrier wavelength, and $T$ is a transpose symbol.

This transmitted scheme can also be interpreted as space-division multiple access (SDMA) mode, where the transmitting node facilitates the communication link with desired receiving node(s) by various spatial virtual sub-channels that are established by the columns of the Butler transmission matrix. Then, for SDMA mode the receiving signal in the *i*th output of the desired receiving node is

$$\mathbf{y} = \sqrt{P^{(d)}}\mathbf{A}_r^{(d)\dagger}\mathbf{H}^{(d)}\mathbf{A}_t^{(d)}\mathbf{s}^{(d)} + \sum_{k=1}^{K}\sqrt{\beta_k P^{(k)}}\mathbf{A}_r^{(d)\dagger}\mathbf{H}^{(k)}\mathbf{A}_t^{(k)}\mathbf{s}^{(k)} + \mathbf{A}_r^{(d)\dagger}\mathbf{n}, \quad (9)$$

where $\beta_k$ is an attenuating interferer factor due to selectivity of space division signatures.

The resulting SINR in the output of the *i*th virtual sub-channel yields

$$\textit{SINR}_i = \frac{P^{(d)}|\mathbf{a}_{r(i)}^{(d)\dagger}\mathbf{H}^{(d)}\mathbf{a}_{t(i)}^{(d)}|^2}{\sum_{k=1}^{K}\sum_{j=1}^{M_r}\beta_k P^{(k)}|\mathbf{a}_{r(i)}^{(d)\dagger}\mathbf{H}^{(k)}\mathbf{a}_{t(j)}^{(k)}|^2 + \mathcal{N}}. \quad (10)$$

As follows from (10), in the SDMA mode in the presence of interferer signals it is preferably of using the beam diversity to maximize SINR in the desired receiver node output. It can be done by selecting the beams with which are not affected by interferers, while the other beams can be used to significantly compensate the interferer signals, as for example, described in [20].

The computational work, according to (9) is $M_t \times log_2 M_t$ complex operations to form the Butler matrix on the transmitter side, and is $M_r \times log_2 M_r$ on the receiver side, plus $M_t$ and $M_r$ complex operations to form the corresponding transmitting and receiving signals. Supposing that transmitter and receiver have the same number of antennae, i.e., $M_T = M_r = M$, the total computational complexity of SDMA implementation is $2M \times log_2 M + 2M$, or shortly $(2M+1)log_2 M$ complex operations.

## 4. Performance in the Presence of CSIT

### 4.1. *Spatial multiplexing with SVD of the channel matrix*

Let us consider the communication scenario where the desired node operates in the presence of $K$ interferer nodes, which can operate in both receiving and transmitting mode as Fig. 3.1 shows. We suppose that the desired receiving node is able to receive the required channel knowledge, i.e., the set of the channel matrixes that directly associated with the desired node, $\{\mathbf{H}^{(d)}, \mathbf{H}^{(1)}, \mathbf{H}^{(2)}, \ldots, \mathbf{H}^{(k)}, \ldots, \mathbf{H}^{(K)}\}$. CSIT can be obtained by establishing $K$ associated feedback links. Despite these links require additional bandwidth, the availability of the CSIT helps both to achieve the deeper than in SDMA mode interferer suppression and to establish eigenmode transmission that enhances the spectral efficiency and increase the resulting SINR.

Let the singular value decomposition of the matrix $\mathbf{H}^{(k)}$ is

$$\mathbf{H}^{(k)} = \mathbf{U}^{(k)}\Sigma^{(k)}\mathbf{V}^{(k)\dagger}, \quad (11)$$

where $\mathbf{U}^{(k)} \in \mathbb{C}^{M_r \times M_r}$ and $\mathbf{V}^{(k)} \in \mathbb{C}^{M_t \times M_t}$ are corresponding receiver and transmitter beamforming matrices with the orthonormal properties, $k = d, 1, 2, \ldots, K$, and $\Sigma^{(k)}$ is a matrix with the singular values entries through the main diagonal.

The desired receiving node output vector in the presence of $K$ interferer transmitter is

$$\mathbf{y} = \sqrt{P^{(d)}}\mathbf{U}^{(d)\dagger}\mathbf{H}^{(d)}\mathbf{V}^{(d)}\Upsilon^{(d)\frac{1}{2}}\mathbf{s}^{(d)} + \sum_{k=1}^{K}\sqrt{P^{(k)}}\mathbf{U}^{(d)\dagger}\mathbf{H}^{(k)}\mathbf{V}^{(k)}\Upsilon^{(k)\frac{1}{2}}\mathbf{s}^{(k)\dagger} + \mathbf{U}^{(d)\dagger}\mathbf{n}. \quad (12)$$

We rewrite (12) with (11) as

$$\mathbf{y} = \sqrt{P^{(d)}}\Sigma^{(d)}\Upsilon^{(d)\frac{1}{2}}\mathbf{s}^{(d)} + \sum_{k=1}^{K}\sqrt{P^{(k)}}\Sigma^{(k)}\mathbf{U}^{(d)\dagger}\mathbf{U}^{(k)}\Upsilon^{(k)\frac{1}{2}}\mathbf{s}^{(k)} + \mathbf{U}^{(d)\dagger}\mathbf{n}. \quad (13)$$

Then, the resulting SINR in the output of the *i*th virtual sub-channel is

$$\textit{SINR}_i = \frac{P^{(d)}\gamma_i^{(d)}\sigma_i^{(d)2}}{\sum_{k=1}^{K}\sum_{j=1}^{M_r}P^{(k)}\gamma_j^{(k)}|\sigma_j^{(k)2}\mathbf{u}_i^{(d)\dagger}\mathbf{u}_j^{(k)}|^2 + \mathcal{N}}. \quad (14)$$

As (14) shows, with CSIT available at the transmitter substantially larger SINR can be achieved than those of the blind transmitter approach, because in reach propagation environment more probably that $\mathbf{u}_i^{(d)\dagger}\mathbf{u}_j^{(k)} \to 0$. However, in the general case $\mathbf{u}_i^{(d)\dagger}\mathbf{u}_j^{(k)} \neq 0$, and the deep suppression of all interference in the output of desired node sometimes is a challenging problem, which partially solved in [21] for mutually three interfering links. Suppression of interferer multipath streams also discussed in [9, 10]

SMSVD transmission mode requires the CSIT to be available from all associated interferer nodes. This information can be sent using feedback facilities, and amount of information is $KM$ matrices, or $KM^2$ complex elements.

The computational work, according to (13) is $K \times 4M^3$ complex operations to compute $K$ times singular value decompositions [16], plus $2M$ complex operations to form the transmitting and receiving signals. Hence, the total computational work is $K \times 4M^3 + 2M$.

### 4.2. *Spatial multiplexing with adaptive beamforming*

Depending on either the signal is received with a certain gain (desired signal), or is perfectly nulled (interferer signal), the strategy of choosing the transmitter

($\mathbf{W}_t$) and receiver ($\mathbf{W}_r$) weights in the beamforming mode are different.

We consider three possible types of relationships between transmitting and receiving nodes [13], which includes either a desired communication pair link that requires to maximize SINR on the receiving node, or undesired potentially interferer link that requires to minimize SINR on the receiving node.

(i) If the receiving node weight vector $\mathbf{W}_r^{(d)}$ is adjusted to desired signal $\mathbf{s}^{(d)}$, which is transmitted by desired transmitting node, then we can choose $\mathbf{W}_t^{(d)}$ to satisfy $\mathbf{W}_r^{(d)\dagger}\mathbf{H}^{(d)}\mathbf{W}_t^{(d)} = \mathbf{I}_{M_r}$.

(ii) If the desired receiving node weight vector $\mathbf{W}_r^{(d)}$ is adjusted to desired signal $\mathbf{s}^{(d)}$, which is transmitted by some desired transmitting node, and in the same time *k*th transmitting node tries to transmit undesirable signal (interferer) toward the desired receiving node, then we chose $\mathbf{W}_t^{(k)}$ such that the transmitting node does not create interference at the receiving node, or $\mathbf{W}_r^{(d)\dagger}\mathbf{H}^{(k)}\mathbf{W}_t^{(k)} = \mathbf{0}$, where $\mathbf{0}_{M_r}$ is a zero square matrix.

(iii) If the desired transmitting node uses the vector $\mathbf{W}_t^{(d)}$, and *k*th receiving nodes vector $\mathbf{W}_r^{(k)}$ is adjusted to suppress the interferer from the desired transmitting node, then $\mathbf{W}_r^{(k)}$ should satisfy $\mathbf{W}_r^{(k)\dagger}\mathbf{H}^{(k)}\mathbf{W}_t^{(d)} = \mathbf{0}$.

The desired receiving node output signal in the presence of $K$ interferer transmitting nodes is

$$\begin{aligned}\mathbf{y} =& \sqrt{P^{(d)}}\mathbf{W}_r^{(d)\dagger}\mathbf{H}^{(d)}\mathbf{W}_t^{(d)}\Upsilon^{(d)\frac{1}{2}}\mathbf{s}^{(d)} \\ &+ \sum_{k=1}^{K}\sqrt{P^{(k)}}\mathbf{W}_r^{(d)\dagger}\mathbf{H}^{(k)}\mathbf{W}_t^{(k)}\Upsilon^{(k)\frac{1}{2}}\mathbf{s}^{(k)} \\ &+ \mathbf{W}_r^{(d)\dagger}\mathbf{n}.\end{aligned} \tag{15}$$

The first term in (15) is the desired signal, while the second one is a collection of all interferer signals in the output of the desired node, which should be suppressed as deeply as possible. The resulting SINR in the output of the *i*th virtual sub-channel is given by

$$\mathit{SINR}_i = \frac{P^{(d)}\gamma_i^{(d)}|\mathbf{w}_{r(i)}^{(d)\dagger}\mathbf{H}^{(d)}\mathbf{w}_{t(i)}^{(d)}|^2}{\sum_{k=1}^{K}\sum_{j=1}^{M_r}P^{(k)}\gamma_j^{(k)}|\mathbf{w}_{r(i)}^{(d)\dagger}\mathbf{H}^{(k)}\mathbf{w}_{t(j)}^{(k)}|^2+\mathcal{N}}. \tag{16}$$

As follows from (16) at the beamforming mode with CSIT substantially larger SINR can be achieved than with any previous discussed implementations, by satisfying of all three cases of relationships between transmitting and receiving nodes discussed here. We analyze the interferer suppression technique just only for a one single transmitting and receiving beam, which corresponds to any eigenvalue of the channel matrix. For other pare of transmitting and receiving beams analysis will be similar. Let the corresponding transmitter and receiver weight vectors are $\mathbf{w}_t^{(k)}$ and $\mathbf{w}_r^{(k)}$. To satisfy the case 1 and the case 2 we suppose that $\mathbf{w}_t^{(k)}$ already fixed in the interferer transmitting nodes, and to find $\mathbf{w}_r^{(d)}$ we need to solve the system of linear equations

$$\begin{aligned}\mathbf{w}_r^{(d)\dagger}\mathbf{H}^{(d)}\mathbf{w}_t^{(d)} &= 1, \\ \mathbf{w}_r^{(d)\dagger}\mathbf{H}^{(1)}\mathbf{w}_t^{(1)} &= 0, \\ &\cdots \\ \mathbf{w}_r^{(d)\dagger}\mathbf{H}^{(K)}\mathbf{w}_t^{(K)} &= 0,\end{aligned} \tag{17}$$

In the matrix form (17) can be rewritten as

$$\mathbf{w}_r^{(d)\dagger}\mathcal{H}_k = \mathbf{q}^T, \tag{18}$$

where $\mathcal{H}_k = \mathbf{H}^{(k)}\mathbf{w}_t^{(k)}$, $k = d, 1, 2, \dots, K$, and $\mathbf{q} = [1, 0, \dots, 0]^T$. The solution of (18) is

$$\mathbf{w}_r^{(d)} = \mathcal{H}_k^{\sharp\dagger}\mathbf{q}, \tag{19}$$

where $\sharp$ is a pseudo inverse matrix sign.

To satisfy the case 3 we suppose that $\mathbf{w}_r^{(k)}$ already fixed in the nearest receiving nodes, and to find $\mathbf{w}_t^{(d)}$ we need to solve another system of linear equations

$$\begin{aligned}\mathbf{w}_r^{(d)\dagger}\mathbf{H}^{(d)}\mathbf{w}_t^{(d)} &= 1, \\ \mathbf{w}_r^{(1)\dagger}\mathbf{H}^{(1)}\mathbf{w}_t^{(d)} &= 0, \\ &\cdots \\ \mathbf{w}_r^{(K)\dagger}\mathbf{H}^{(K)}\mathbf{w}_t^{(d)} &= 0.\end{aligned} \tag{20}$$

Similarly, (20) in the matrix form is

$$\mathcal{Q}_k\mathbf{w}_t^{(d)} = \mathbf{q}, \tag{21}$$

where $\mathcal{Q}_k = \mathbf{w}_r^{(k)}\mathbf{H}^{(k)}$, $k = d, 1, 2, \dots, K$. The corresponding solution of (21) is

$$\mathbf{w}_t^{(d)} = \mathcal{Q}_k^{\sharp}\mathbf{q}, \tag{22}$$

Afterward, the resulting weight vectors should be normalized as $\mathbf{w}_r^{(d)}\left(\mathbf{w}_r^{(d)\dagger}\mathbf{w}_r^{(d)}\right)^{-1/2}$ and $\mathbf{w}_t^{(d)}\left(\mathbf{w}_t^{(d)\dagger}\mathbf{w}_t^{(d)}\right)^{-1/2}$ in order to achieve the 2-norms of $\mathbf{w}_r^{(d)}$ and $\mathbf{w}_t^{(d)}$ to be equal to the unit.

SMAB as well as SMSVD also requires the CSIT to be available from all associated interferer nodes, and amount of feedback information is the same, i.e., $KM^2$ elements. The computational work, according to (15) is $K \times 4M^3$ complex operations to compute $K$ times singular value decompositions, plus $2b \times 4M^3$ complex operations to implement (19) and (22), where $b$ is a number of beams, plus $2M$ complex operations to form the transmitting and receiving signals. Hence, the total computational work is $K \times 4M^3 + 2b \times 4M^3 + 2M$.

## 5. Simulation Result

We use numerical examples to control the output SINR and corresponding symbol error rate (SER) of desired receiving node and different transmission schemes in use. We set $M_t = M_r = 4$ for all nodes and configuring transmitting and receiving antennas as uniform linear array (ULA) of omnidirectional vertical dipoles with the distances between them $d = \lambda/2$. A multipath propagation environment is assumed. The desired receiving node is operating in the presents of two neighboring interferer nodes, hence, the propagation matrices are $\{\mathbf{H}^{(d)}, \mathbf{H}^{(1)}, \mathbf{H}^{(2)}\}$, and they has been generated using (1). The 16-QAM modulation constellation is used for symbols mapping. Simulation was carried out with four different transmitting schemes discussed above, namely

(i) Blind transmission with space time coding (BT-STC). This transmission scheme uses four omnidirectional antennas and data are transmitted using space time code with the length equals four [22].

(ii) Spatial multiplexing with the Butler matrix (SDMA). Transmitter uses the Butler matrix to process the input data. The resulting transmitting pattern presented in Fig. 3, which shows four spatial orthogonal patterns in the range of the azimuth angle $\theta$, $-\pi \ldots \pi$ in radians, or -1 … 1 as a $sin(\theta)$. Because of high level of the pattern side lobes, $-13\ dB$, the Butler matrix was weighted using Chebychev window [23], achieving the side lobes level $-40\ dB$, however, sacrificing the main lobe width. The resulting transmitting pattern with the weighted Butler matrix presented in Fig.4,

(iii) Spatial multiplexing with SVD of channel matrix and dominant eigenmode beamforming (SMSVD). The antenna pattern in this case transmits in the direction determined by dominant eigenvector and resulting pattern presented in Fig. 5 as nonadaptive pattern.

(iv) Spatial multiplexing and adaptive beamforming with dominant eigenmode transmission (SMAB). This type of beamforming allows to suppress the interferer signals using adaptive algorithm (18) providing the higher performance and the resulting pattern presented in Fig. 5 as adaptive pattern.

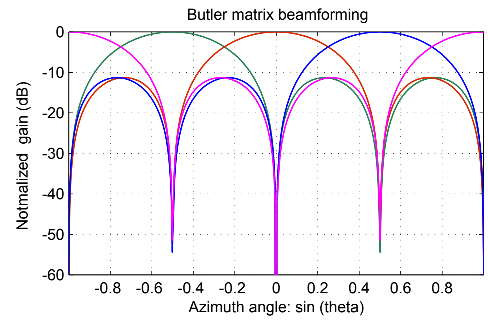


Fig. 3. Four spatial orthogonal patterns formed by Butler matrix.

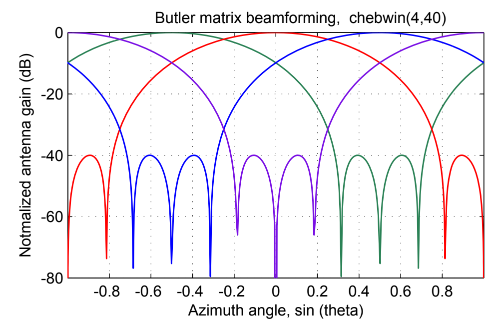


Fig. 4. Four spatial orthogonal patterns weighted with Chebyshev window.

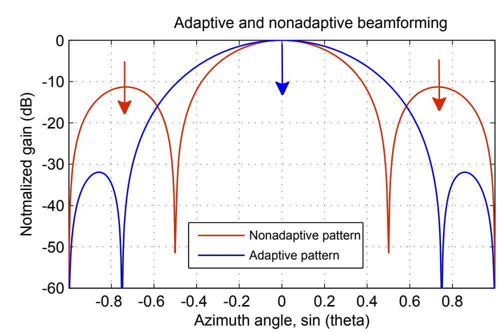


Fig. 5. Patterns formed by dominant eigenvector. Directions of arrival of desired and interferer signals are $\theta_d = 0$, and $\theta_k = \pm 0.7$, respectively.

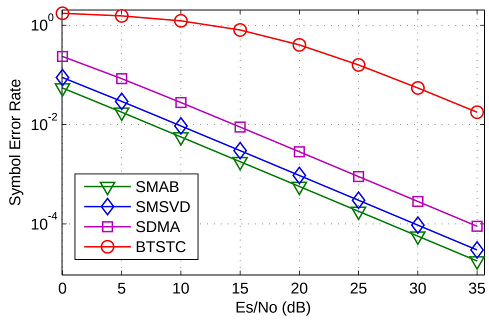


Fig. 6. MIMO ad hoc node performance for different implementations.

Resulting performance benchmarks, SER vs. the ratio $E_s/\mathcal{N}$, of the BTSTC, SDMA, SMSVD and SMAB for a single spatial virtual sub-channel is presented in Fig.6. As Fig. 6 shows, to achieve $SER = 10^{-4}$ the required ratios $E_s/\mathcal{N}$ for SMAB, SMSVD, SDMA, and BTSTC are 27.5 $dB$, 29.6 $dB$, 34.3 $dB$ and 55.5 $dB$, respectively. Therefore, SMAB possess the best performance, which has $E_s/\mathcal{N}$ gain over SMSVD, SDMA, and BTSTC approximately 2.1 $dB$, 6.9 $dB$, and 28.0 $dB$, respectively. However, enormous computational work and huge amount of required feedback information can be considered as a high cost of the achieved performance gain. The gap between SMSVD and SMAB is only 2.1 $dB$, however, the computational complexity as less as $\sim (K + 2b)$. SDMA do not need feedback facilities, but performance gain degradations is 6.9 $dB$, that could be accepted for many applications. Detailed comparative analysis of four presented MIMO link implementations presented in Table 1.

| MIMO link implementations | Performance, SER(dB) | Computational complexity | Feedback cost |
|---|---|---|---|
| BTSTC | 55.5 | $2M$ | 0 |
| SDMA | 34.3 | $(2M+1)log_2M$ | 0 |
| SMSVD | 29.6 | $4M^3+2M$ | $KM^2$ |
| SMAB | 27.5 | $(K+2b)4M^3+2M$ | $KM^2$ |

Table 1. Comparison of MIMO ad hoc link implementations.

## 6. Conclusions

We have analyzed and discussed more popular MIMO ad hoc wireless network implementations, such as, blind transmission mode with space time coding (BTSTC), spatial multiplexing with the Butler matrix beamforming (SDMA), spatial multiplexing with SVD of channel matrix (SMSVD), and spatial multiplexing with adaptive beamforming (SMAB). We did the comparative analysis involving such criteria as a peer-to-peer link performance, computational complexity and required feedback information. The performance was estimated analytically (SINR) as well as by simulation (SER). The obtained result shows that for a general communication scenario SMAB has performance advantage over SMSVD, SDMA, and BTSTC. The power gain is approximately 2.1 $dB$, 6.9 $dB$, and 28.0 $dB$, respectively. Poor performance of BTSTC can be explained by absence of spatial diversity between desired and interferer nodes. Despite SDMA has a lost 6.9 $dB$, this transmission mode can be considered as quite attractive for implementations due to low computational work and lack of feedback channels. SMAB achieve the highest performance, however, for weight vector adjustment in each virtual sub-channel it requires high cost computing adaptive algorithm with the complexity $(K+2b)4M^3+2M$, which makes the implementation less attractive that SMSVD or SDMA.

## References

[1] S. K. Sarkar, T. G. Basavaraju, and C. Puttamadappa. *Ad hoc mobile wireless networks : principles, protocols, and applications*. Auerbach Publications, 2008.

[2] A. Boukerche, editor. *Algorithms and protocols for wireless, mobile ad hoc networks*. John Wiley and Sons, Inc, 2009.

[3] B. Tavli and W. Heinzelman. *Mobile Ad Hoc Networks Energy Efficient Real Time Data Communications*. Springer, 2006.

[4] B. Chen and M. J. Gans. Mimo communications in ad hoc networks. *IEEE Trans. Signal Proc.*, 54(7):2773–2783, July 2007.

[5] S. Chu, X. Wang, and Y. Yan. Adaptive scheduling in mimo-based heterogeneous ad hoc networks. *IEEE Transactions on Mobile Computing*, 13(5):964–978, 2014.

[6] G. J. Foschini and M. J. Gans. On limits of wireless communications in a fading environment when using multiple antennas. *Wireless Personal Communications*, 6:311–335, 1998.

[7] G. Tsoulos, editor. *MIMO system technology for wireless communications*. Taylor Francis Group, 2006.

[8] E. Telatar. Capacity of multi antenna gaussian channels. *Trans. Telecomm.*, 10:585–595, Nov.-Dec. 1999.

[9] V. Zaharov, A. Lambertt, and O. Polyanska. *Innovations and Advances in Computing, Informatics, Systems Sciences, Networking and Engineering*, volume 313, chapter Stream Collision Management in MIMO Ad-Hoc Network Sustaining the Lower Bound of QoS, pages 47–52. Springer, 2015.

[10] M.F. Demirkol and M.A. Ingram. Stream control in networks with interfering MIMO links. In *IEEE Wireless Communications and Networking Conf.*, volume 1, pages 343–348, March 2003.

[11] V. Kühn. *Wireless Communications over MIMO Channels, Applications to CDMA and Multiple Antenna Systems*. John Wiley & Sons, 2006.

[12] L. Zheng and D. N. Tse. Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels. *EEE Transactions on Information Theory*, 49(5):1073–1096, 2003.

[13] J. C. Mundarath, P. Ramanathan, and B. D. Van Veen. A cross layer scheme for adaptive antenna array based wireless ad hoc networks in multipath environments. *Wireless Netw*, 13:597–615, 2007.

[14] S. V. Bana and P. Varaiya. Space division multiple access (sdma) for robust ad hoc vehicle communication networks. In *Intelligent Transportation Systems*, pages 962–967, Aug 2001.

[15] M. Jankiraman. *Space Time Codes and MIMO Systems*. Artech House, 2004.

[16] G. Golub and C. Van Loan. *Matrix Computations*. Baltimore, MD: The John Hopkins Univ. Press, 3rd edition, 1996.

[17] T. Cover and J. Thomas. *Elements of Information Theory*. New York: John Wiley and Sons, 1992.

[18] V. Tarokh, H. Jafarkhani, and A. Calderbank. Space time block coding for wireless communications: performance results. *IEEE Journal on Selected Areas in Communications*, 17(3):451–460, March 1999.

[19] A.J.Paulraj, R. Nabar, and D. Gore. *Introduction to Space-Time Wireless Communications*. Cambridge University Press, UK, 2003.

[20] H. Van Trees. *Detection, Estimation, and Modulation Theory. Part IV, Optimum Array Processing.* New York: Wiley, 2002.

[21] V. R. Cadambe and S. A. Jafar. Interference alignment and degrees of freedom of the k-user interference channel. *IEEE Trans. on Information Theory*, 54(8):3425–3441, August 2008.

[22] G. Ganesan and P. Stoica. Space time block codes: A maximum snr approach. *IEEE Transactions on Information Theory*, 47(4):1650–1656, 2001.

[23] S L Marple. *Digital Spectral Analysis with Application*. Prentice-Hal, 1987.