Rate Maximization in Dense Interference Networks Using Non-Cooperative Passively Loaded Relays

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***Abstract*— Concepts like the internet of things (IOT) and heterogeneous networks would allow large communication node densities. In such scenarios, the communication system performance is usually interference limited. Classical methods for interference management are either inefficient with regards to spectral efficiency or consume much power. However, in such scenarios nodes may be very near to each other in terms of wave length. Hence, there would have antenna coupling between them, which adds a new domain to the problem. We consider a communication system with multiple single antenna transmitter-receiver pairs, forming an interference channel. The receivers are closely spaced and surrounded by a number of non-cooperative passively loaded relays. Receive antennas and relay antennas experience coupling between each other. We adapt the relay loads as well as the matching networks of the receivers to maximize the sum rate. Our results show huge performance enhancements in comparison to TDMA. In some cases, they are close to the ones having multiple antenna receivers that use the theoretically best multiport matching. Our proposed algorithm is relevant to modern communication systems with high node density.**

I. Introduction

With the massive increase of wireless devices as well as wireless applications, the density of communication nodes and antennas per area is expected to increase. There are multiple scenarios where there is a large number of antennas in the close physical vicinity. For example, future systems adopting approaches like the internet of things (IOT) [1] and heterogeneous networks with multiple closely spaced nodes communicating with other nodes that may be far away. Another example is the service of multiple mobile users in a highly crowded area, such as a stadium or a festival. In these setups, interference plays a major role in the system performance.

We consider M single-antenna transmitter-receiver pairs which are communicating simultaneously. The transmitters are widely spaced and far from the receivers. However, the receivers are closely spaced and surrounded with L relays as shown in Fig. 1. These relays could be dedicated devices or simply inactive users. All the receivers and relays are *non-cooperative*. By non-cooperative we mean that they do not share their received data together. Managing interference in this scenario is very critical. Classical methods based on resource *orthogonalisation* such as TDMA, FDMA, CDMA and OFDMA can be applied, however their throughput decreases drastically as M increases. A different concept is the so-called distributed spatial multiplexing (DSM), in which relays are used [2]. The gain matrix of the relays is designed to either completely zero force (ZF) interference or to minimize the minimum mean square error criteria. Depending on M and the total number of antennas per relay, the number of relay required is calculated [3]. However, such techniques need additional transmit power consumption and two time slots to deliver messages to the receivers, which may not be preferable. Another solution to the interference problem, is to allow nodes to fully cooperate. Although this would allow successful interference management, it would drastically increase the complexity and the power consumption. This comes from the fact that a considerable amount of time and power is wasted in the data transfer between the nodes.

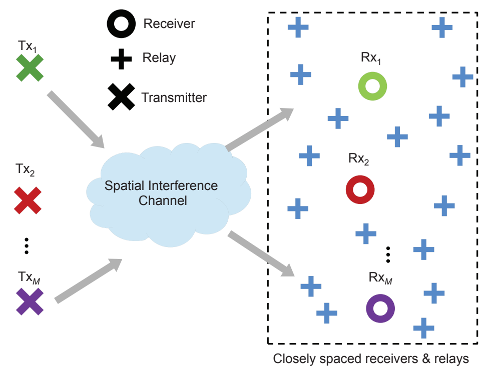

Fig. 1. System schematic.

The scenario at hand has a very special characteristic which adds a new dimension of interest to it. Due to small distances in terms of wave length λ between the nodes at the side of the receivers and relays, antenna coupling between the antennas is present. To correctly characterize the system, a description based on circuit theory [4], [5] has to be used. In general, antenna coupling changes the system characteristics strongly, since it introduces impedance miss-match, change of the signal properties as well as change in the noise properties. Research relevant to scenarios with coupled antennas was done along the following two lines:

- Matching network (MN) design: In MIMO system with strongly coupled antennas, the signal properties as well as the noise properties have large dependency on the matching strategy used. Different algorithms were suggested for designing the uncoupled (UC) MN to enhance the performance, e.g. [6], [7], [8], [9]. However they were concerned with *one receiver having co-located antennas*

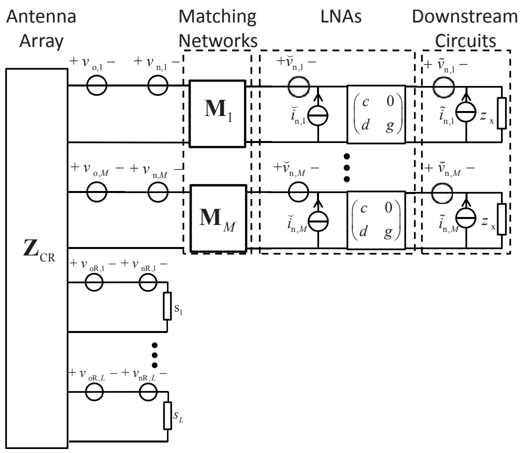

Fig. 2. Circuit schematic of the receivers and the relays.

in an interference free multi user (MU)- MIMO scenario.

- Use of *parasitic* antennas: A parasitic antenna is an antenna terminated by a load (maybe adaptive) that is placed closely to transmitting or receiving antennas. The use of parasitic antennas is as old as the invention of the Yagi antennas [10]. In the previous years, it had gained more interest from communication theory point of view. In [11], a MIMO transmission based on having a single-RF fed antenna surrounded by data dependent adaptively loaded parasitic antennas has been introduced. By this approach, different data streams could be sent on the spatial domain. In [12], parasitic antennas are placed near to a receive antenna. Using load switching a 360° rotating antenna beam is realized. A different application of the parasitic antennas was presented in [13], where a parasitic antenna is placed between two coupled dipoles with its load selected to decouple the two antennas.

Capitalizing on antenna coupling, we adapt the relay loads as well as the components of the MNs to enhance the sum rate of this interference network. Hence, *it is not consuming transmit power*. We assume full knowledge of the spatial channels and the coupling matrix. This can be done in the training phase using the algorithm proposed in [14]. Our results show strong performance enhancement in comparison to the TDMA approach. In some cases, the performance is even very close to the ones with multiple antennas per receiver with either widely spaced antennas or with coupled ones that use the theoretically best multiport matching [4], [5]. In summary: *We combine concepts from communication theory such as DSM with such from circuits such as MN optimization and parasitic antennas to enhance the performance in dense interference networks*.

II. System Model

In this section we are going to use the circuit model describing the receivers and the relays shown in Fig. 2. Our main target is to have an input-output relationship that maps the generator voltages $\mathbf{v}_\mathrm{G} \in \mathbb{C}^{M\times 1}$ to the vector of the load voltages $\mathbf{v}_\mathrm{L} \in \mathbb{C}^{M\times 1}$ at the receivers in the following way:

$$\mathbf{v}_\mathrm{L} = \mathbf{A}\mathbf{v}_\mathrm{G} + \mathbf{u}_\mathrm{N}, \tag{1}$$

where the matrix $\mathbf{A} \in \mathbb{C}^{M\times M}$ is the equivalent channel matrix and the vector $\mathbf{u}_\mathrm{N} \in \mathbb{C}^{M\times 1}$ is the vector of noise at the receivers which has a covariance matrix $\mathbf{R}_\mathrm{N} = \mathrm{E}[\mathbf{u}_\mathrm{N}\mathbf{u}_\mathrm{N}^H]$. To do so, we are going to revisit some of the system equations that were used in [4], [9].

A. Different Circuit Components

The first component at the receivers and relay side is the lossless antenna array. From circuit theory, the antenna array is usually modeled by its *symmetric* impedance matrix $\mathbf{Z}_\mathrm{CR} \in \mathbb{C}^{L+M\times L+M}$ [10]. The external noise $\mathbf{v}_\mathrm{n}$ captured by the radiation component of the antenna array is correlated and has a noise covariance matrix $\mathbf{R}_\mathrm{na}$ which is directly proportional to the real part of $\mathbf{Z}_\mathrm{CR}$ [4].

Each receiver i has a *lossless and reciprocal* MN $\mathbf{M}_i$ with *pure imaginary* adaptive components. This MN is defined using the impedance parameters as

$$\mathbf{M}_i = \begin{bmatrix} z_{\mathrm{M}11,i} & z_{\mathrm{M}12,i} \\ z_{\mathrm{M}12,i} & z_{\mathrm{M}22,i} \end{bmatrix}. \tag{2}$$

Each relay j has a load impedance S_j. We restrict the load impedances of the relays to be pure imaginary so that they are lossless and do not contribute to the noise.

The upcoming stages at the receivers are the LNA and the downstream parts [5]. Each LNA has two noise sources at its input [4], a series voltage source $\breve{v}_n$ and a parallel current source $\breve{i}_n$. The noise sources having the statistical properties $\mathrm{E}[\breve{\mathbf{i}}_n\breve{\mathbf{i}}_n^H] = \breve{\beta}\mathbf{I}_M$, $\mathrm{E}[\breve{\mathbf{v}}_\mathrm{n}\breve{\mathbf{v}}_\mathrm{n}^H] = \breve{\beta}\breve{R}_\mathrm{n}^2\mathbf{I}_M$ and $\mathrm{E}[\breve{\mathbf{v}}_\mathrm{n}\breve{\mathbf{i}}_n^H] = \breve{\rho}\breve{\beta}\breve{R}_\mathrm{n}\mathbf{I}_M$. The impedance matrix of the LNA is defined as $\mathbf{Z}_\mathrm{LNA} = \begin{bmatrix} c & 0 \\ d & g \end{bmatrix}$. The downstream circuits part has the load impedance z_x and two noise sources, namely $\tilde{\mathbf{v}}_\mathrm{n}$ and $\tilde{\mathbf{i}}_\mathrm{n}$, to account for the noise from other circuitry components that do not flow back to the antennas. They have the following characteristics: $\mathrm{E}[\tilde{\mathbf{i}}_n\tilde{\mathbf{i}}_n^H] = \tilde{\beta}\mathbf{I}_M$, $\mathrm{E}[\tilde{\mathbf{v}}_\mathrm{n}\tilde{\mathbf{v}}_\mathrm{n}^H] = \tilde{\beta}\tilde{R}_\mathrm{n}^2\mathbf{I}_M$ and $\mathrm{E}[\tilde{\mathbf{v}}_\mathrm{n}\tilde{\mathbf{i}}_n^H] = \tilde{\rho}\tilde{\beta}\tilde{R}_\mathrm{n}\mathbf{I}_M$.

B. Incorporating the Relays in the Matrix $\mathbf{A}$

The equivalent channel matrix $\mathbf{A}$ defined in equation (1) captures the effects of the receiver circuitry, the spatial channel and transmitters circuitry and has the following form

$$\mathbf{A} = \mathbf{G}_\mathrm{R}\mathbf{Z}_\mathrm{SR}\sqrt{\alpha}. \tag{3}$$

The value $\sqrt{\alpha}$ captures the circuitry effects at the uncoupled and widely spaced transmitters. The transimpedance matrix $\mathbf{Z}_\mathrm{SR} \in \mathbb{C}^{L+M\times M}$ models the spatial channel between the transmitters, the receivers and the relays. The signal open circuit voltages at the receiver and relay antennas are equal to $\mathbf{v}_\mathrm{oT} \in \mathbb{C}^{L+M\times 1}$

$$\mathbf{v}_\mathrm{oT} = \overbrace{\mathbf{R}_\mathrm{RX}^{\frac{1}{2}}\mathbf{Z}_\mathrm{P}}^{\mathbf{Z}_\mathrm{SR}}\sqrt{\alpha}\mathbf{v}_\mathrm{G}. \tag{4}$$

The entries of the matrix $\mathbf{Z}_\text{P}$ are independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance. The spatial correlation matrix at the receiver is denoted by $\mathbf{R}_\text{RX}$. The last part of matrix $\mathbf{A}$ is the matrix $\mathbf{G}_\text{R} \in \mathbb{C}^{M \times L+M}$ which captures the effects of circuitry at the receiver side.

There are different ways to calculate the matrix $\mathbf{G}_\text{R}$. We resort to using the same equations as in [9], in which co-located antennas are considered. In order to easily incorporate the effects of the relays we use the following trick: We assume that the relays are also receiver antennas but with a specific MN. In [4], [9], the whole matching stage is represented by a large multiport of size $2(L+M) \times 2(L+M)$ which has the following impedance parameters

$$\mathbf{Z}_\text{M} = \begin{bmatrix} j\mathbf{Z}_{11} & j\mathbf{Z}_{12} \\ j\mathbf{Z}_{12} & j\mathbf{Z}_{22} \end{bmatrix}, \tag{5}$$

where all the matrices $\mathbf{Z}_{11}$, $\mathbf{Z}_{12}$ and $\mathbf{Z}_{22}$ are diagonal and related to the elements of the individual MNs of each receiver as described in [9]. We set the $z_{\text{M12},j} = 0 \quad \forall \quad j \in \{M+1, \ldots, L+M\}$. This means that it is a receiver with isolated RF front end. We would also set the $z_{\text{M22},j} = s_j \quad \forall \quad j \in \{M+1, \ldots, L+M\}$. The value of $z_{\text{M11},j}$ is irrelevant for all values of j. After using this trick, we can use the same equations as in [4], [9] to derive the matrix $\mathbf{G}_\text{R}$ as well as $\mathbf{R}_\text{N}$. Note that in [9], the effects of the circuits on the signal were given as a product of two matrices which we call here $\tilde{\mathbf{A}} \in \mathbb{C}^{L+M \times L+M}$ and define as

$$\tilde{\mathbf{A}} = \mathbf{D}\mathbf{F}_\text{R}. \tag{6}$$

Using our proposal, the matrix $\mathbf{G}_\text{R}$ in our case is the upper matrix of size $M \times L+M$ of the matrix $\tilde{\mathbf{A}}$ in [9], *which heavily depends on the elements of the MNs and the relay loads*. The relationship between the circuit components and the matrices $\mathbf{D}$, $\mathbf{F}_\text{R}$ and the noise covariance matrix $\mathbf{R}_\text{N}$ can be found in the appendix.

III. Optimization Problem

In our system, we assume that all the transmitters are far away from the receivers with same large scale fading effects and same transmission power, i.e. $\text{E}[\mathbf{v}_\text{G}\mathbf{v}_\text{G}^H = P\mathbf{I}_M]$, where $\mathbf{I}_M$ is the identity matrix. Without loss of generality, we will assume that transmitter i is transmitting to receiver i. Hence, at receiver i all the other signals from the other transmitters $j \quad \forall \quad j \in \{1, 2, \ldots, M\} \setminus \{i\}$ are interference. The load voltage at receiver i is given by

$$v_\text{L,i} = a_{i,i} v_\text{G,i} + \sum_{j=1, j\neq i}^{M} a_{i,j} v_\text{G,j} + u_{\text{N},i}, \tag{7}$$

where $a_{i,j}$ is the coefficient in the i^th row and j^th column of the matrix $\mathbf{A}$ defined in (1). As it can be seen from equation (7), the rate of each user i in bits per channel use (bpcu) becomes

$$r_i = \log_2 \left(1 + \frac{|a_{i,i}|^2 P}{P \sum\limits_{j=1, j\neq i}^{M} |a_{i,j}|^2 + \mathbf{R}_{\text{N},i,i}} \right), \tag{8}$$

where $\mathbf{R}_{\text{N},i,i}$ is the noise power at the receive antenna i. Hence, the sum rate of the whole system is

$$R_\text{s} = \sum_{i=1}^{M} r_i. \tag{9}$$

Since the matrices $\mathbf{A}$ and $\mathbf{R}_\text{N}$ are functions of the MNs and relay load impedances, so become the individual rates and accordingly the sum rate R_s. This leads to our target optimization function

$$\begin{aligned} \underset{\mathbf{M}_1,\ldots,\mathbf{M}_M,S_1,\ldots,S_L}{\text{maximize}} \quad & R_\text{s}(\mathbf{M}_1, \ldots, \mathbf{M}_M, S_1, \ldots, S_L) \\ \text{subject to} \quad & \mathbf{M}_i = \mathbf{M}_i^T, \quad \forall \quad i = 1, \ldots, M \\ & \mathbf{M}_i \quad \forall \quad i = 1, \ldots, M \text{ are imaginary} \\ & S_j \quad \forall \quad j = 1, \ldots, L \text{ are imaginary.} \end{aligned} \tag{10}$$

We assume full knowledge of the spatial channels $\mathbf{Z}_\text{SR}$ and the circuit properties. Recently, an algorithm was proposed to jointly estimate $\mathbf{Z}_\text{SR}$ and $\mathbf{Z}_\text{CR}$ in [14]. Such an algorithm is based on adaptively changing the MNs of the antennas of interest. In this case, each antenna of interest - even a passive relay - is required to perform channel estimation and feed back its estimate to a central unit. However, in the communication phase the relay only adapt its *imaginary* load impedance.

The optimization problem defined in (10) is a non-convex one due to the fact that the matrix $\mathbf{A}$ is related to the components of the MNs and the relay load impedances by an inverse operation [9]. We solve our optimization problem using a gradient ascent algorithm with multiple initializations to try to circumvent the non-convexity problem. Note that the number of parameters V of the optimization problem is $V = 3M + L$. For high M and L, the number of optimization parameters increase making the problem harder to solve. One reason for that is the fact that the problem is non-convex, with huge performance differences between the local optima. Hence, as V grows, the number of local optima grows and more initializations are needed to have a satisfactory result.

IV. System Setup and Performance Evaluation

In our simulations, we assume that the M receivers are distributed uniformly in a square with side length $M\lambda$. We assume that L is an integer multiple of M. We use $\lambda/2$ coplanar parallel dipoles for which $\mathbf{Z}_\text{CR}$ can be calculated using the formulas in [10]. The variable γ denotes the signal to noise ratio (SNR). The entries of the correlation matrix $\mathbf{R}_\text{RX}$ defined in (4) are given as $\mathbf{R}_{\text{RX},ij} = J_0(2\pi d_{i,j}/\lambda)$, where $d_{i,j}$ is the physical separation distance between the i^{th} and j^{th} antenna, and J_0 is the first kind Bessel function of order 0. We assume that the downstream noise is the dominant source. This means that the noise is spatially uncorrelated and is not affected by the relay loads and the MNs. We choose the value of the input impedance of the LNA $c = 75\Omega$. The other remaining circuit parameters are chosen to satisfy the value of the SNR. We define the SNR as the average received SNR when $M = 1$.

In the following we are going to refer to our proposed solution by Opt. We select the following four reference cases to compare our performance to their:

- Ref1: The normal interference channel with no relays.
- Ref2: Applying TDMA. Since we have single antenna transmitters and receivers, there is no solution to the interference problem that is based on beam forming. The only solutions which do not involve the addition of new nodes or antennas are the ones based on orthogonalization schemes like TDMA and other similar techniques.
- Ref3: We consider when we remove the effects of coupling and correlation, i.e. $\mathbf{Z}_{\mathrm{CR}}$ and $\mathbf{R}_{\mathrm{Rx}}$ are both diagonal matrices. We increase the number of antennas at each to $1 + L/M$ and remove the relays.
- Ref4: We consider a scenario similar to Ref3. However, we consider that each receiver has $1+L/M$ antennas that may be closely spaced and hence coupled. The receiver uses the *theoretically* optimal multiport matching [4].

Both Ref3 and Ref4 would serve as our upper limit as they both have higher number of antennas per receiver. *Practically, Ref3 is similar to the case where the relays and ther receiver are far apart and fully cooperating. In reality, this case would come hand in hand with large overheads of data sharing as well as power consumption. Ref4 serves as the optimal case of having at each receiver larger number of antennas and optimal MN. This would increase the receiver complexity, power consumption and physical size. However, this all may not be preferable for systems with nodes that are energy efficient and simple.*

A. Performance for $M = 2$ and $L = 6$

We first consider the case of having $M = 2$ transmit-receive pairs and $L = 6$ passive relays. In this case, 3 relays are distributed randomly around each receiver on a circle of radius 0.1λ. The CDFs of R_{s} using different techniques are plotted in Fig. 3 for $\gamma = 0$ dB. As it can be seen, Ref1 yields a median sum rate of 1.1 bpcu, while Ref2 yields a median sum rate of 0.82 bpcu. The performance using Ref1 which is the interference channel is better than the one of using TDMA in Ref2. The reason behind this observation is the fact that at $\gamma = 0$ dB, the system is more noise limited. Hence, the TDMA would suffer more due to the $1/2$ pre-log factor. In case of using our proposed algorithm (Opt), we can achieve a median sum rate of 3.56 bpcu, which is 223% larger than the case of using Ref1. Moreover, the two curves which we consider as our upper limits would yield median sum rates of 3.91 and 4.21 bpcu for Ref3 and Ref4, respectively.

We now move to the case of $\gamma = 18$ dB plotted in Fig. 4. As it can be seen, the Ref1 curve is very poor leading to a median sum rate of 2.35 bpcu, since the interference power is large. The TDMA performance is a little bit better, and has a median sum rate of around 5.32 bpcu. If our proposed algorithm is used, the median rate is around 14 bpcu. Which is very close to the case of having the two upper limits of Ref3 and Ref4. Note that in the Ref3 and Ref4 cases, each receiver has 4 antennas and suffers from one interfering source. This means that it could easily project the signal on to the null space of the interference and decode it.

B. Performance for $M = 4$ and $L = 28$

Next, we consider the case of having $M = 4$ transmit-receive pairs and $L = 28$ passive relays. We also have $L/M = 7$ relays surrounding each receiver. They are located randomly on a circle of radius 0.26λ. The performance of the proposed algorithm for $\gamma = 0$ dB, can be seen in Fig. 5. Similar to the case of $M = 2$, Ref1 is better than the Ref2 due to the fact that we are in a more noise dominant regime. Ref1 yields a median sum rate of 1.22 bpcu, while our proposed algorithm results in a much larger median sum rate of 6.548 bpcu. The two upper limit curves Ref3 and Ref4 yield a median sum rate of about 10.4 bpcu.

As it can be seen from the performance curves for $\gamma = 18$ dB in Fig. 4, the Ref1 curves are very bad and they are worse than for the case of $M = 2$. This is attributed to the fact that the number of interfering sources increased. For Ref2 we get a median sum rate of around 5.26 bpcu. However, when we use our proposed algorithm, we get a median sum rate of 18.6 bpcu. For the Ref3 and Ref4 cases considered as upper limits, we get approximately the same median sum rate of 32.4 bpcu. There are different reasons for the performance gap between our proposed algorithms and Ref3 and Ref4 for both the cases of $\gamma \in \{0, 18\}$dB. One of these reasons is the fact that the relays are placed not so close to the antenna of the receiver. Hence, we do not get very strong back scattered signals from the relays to the receive antenna and thus the ability to combat the interference decreases. Another conjecture for the gap in the case of $\gamma = 18$ dB, is the fact that we are not capable of minimizing all the interference at all the users at the same time. Another important reason is the fact that in Ref3 and Ref4, each receiver has 8 antennas which are much more than the 3 interfering sources. This makes the upper limits larger.

V. Conclusion

We proposed a novel algorithm to use the coupled antennas in vicinity of an active receiver as passive relays. Our algorithm is completely based on adaptive loading of such passive relays. Hence, it *neither needs any transmit power nor multiple time slots to minimize the effect of the interference*. The results showed substantial performance enhancements with respect to classical solutions such as TDMA. The performance gap between our proposed algorithm and the *much more complex and power hungry* upper bound scenarios we defined is not large in some cases. We view our algorithm as a strong candidate for energy efficient networks, where a small complexity of the communicating nodes is preferred.

Appendix

In the following we are going to summarize the relationship between the different circuit components and the matrix $\tilde{\mathbf{A}}$ defined in equation (6). We are going to stick to the general case in which we assumed that the relay nodes are normal receivers with MNs and use formulas similar to those in

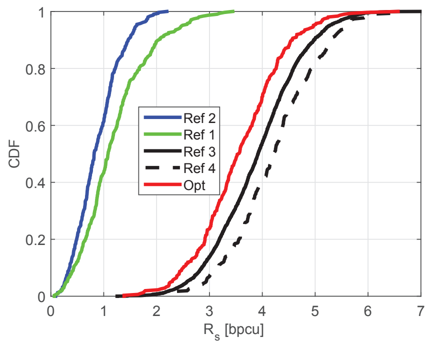

Fig. 3. CDF of the sum rate R_s for $M = 2$, $L = 6$ and $\gamma = 0$dB.

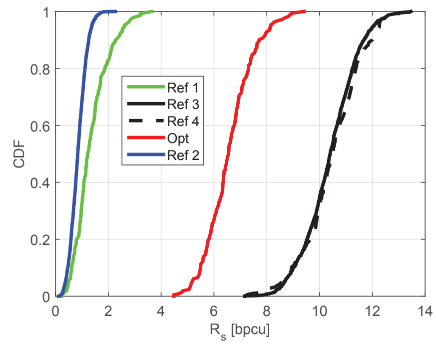

Fig. 5. CDF of the sum rate R_s for $M = 4$, $L = 28$ and $\gamma = 0$dB.

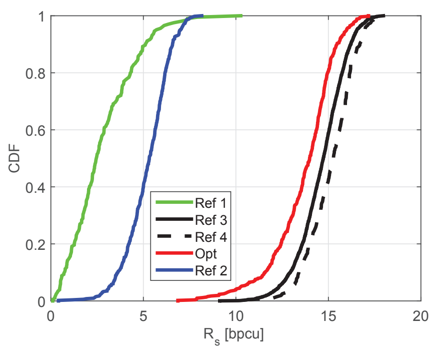

Fig. 4. CDF of the sum rate R_s for $M = 2$, $L = 6$ and $\gamma = 18$dB.

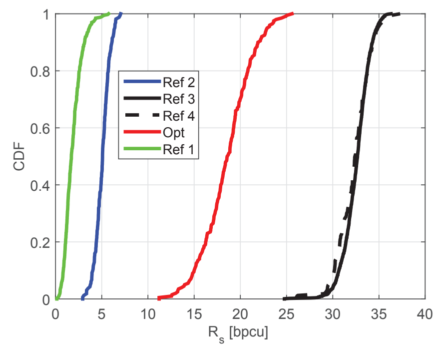

Fig. 6. CDF of the sum rate R_s for $M = 4$, $L = 28$ and $\gamma = 18$dB.

[4], [9]. The first important quantity to define is the input impedance looking into the MNs

$$\mathbf{Z}_{\mathrm{R}} = j\mathbf{Z}_{11} + \mathbf{Z}_{12}(j\mathbf{Z}_{22} + \mathbf{Z}_{\mathrm{CR}})^{-1}\mathbf{Z}_{12} = j\mathbf{Z}_{11} + \mathbf{F}_{\mathrm{R}}\mathbf{Z}_{12}. \quad (11)$$

The other matrix needed is the matrix $\mathbf{D}$ which is equal to

$$\mathbf{D} = j\frac{dz_{\mathrm{x}}}{z_{\mathrm{x}} + g}(c\mathbf{I}_M + \mathbf{Z}_{\mathrm{R}})^{-1}. \quad (12)$$

The covariance matrix of the noise voltages $\mathbf{u}_{\mathrm{N}}$ is given as $\mathbf{R}_{\mathrm{N}} = \zeta\mathbf{D}\mathbf{\Phi}\mathbf{D}^H$, where $\zeta = |dz_{\mathrm{x}}|^2 / |z_{\mathrm{x}} + g|^2$ and the matrix $\mathbf{\Phi}$ defined as

$$\mathbf{\Phi} = \overbrace{\breve{\beta}\left(\mathbf{Z}_{\mathrm{R}}\mathbf{Z}_{\mathrm{R}}^H - 2\breve{R}_{\mathrm{n}}\Re\{\breve{\rho}^*\mathbf{Z}_{\mathrm{R}}\} + \breve{R}_{\mathrm{n}}^2\mathbf{I}_M\right)}^{\text{LNA noise}} + \overbrace{\mathbf{F}_{\mathrm{R}}\mathbf{R}_{\mathrm{na}}\mathbf{F}_{\mathrm{R}}^H}^{\text{Ant. noise}} + \underbrace{\frac{1}{|d|^2}\mathbf{D}^{-1}\psi\mathbf{I}_M\mathbf{D}^{-H}}_{\text{IID noise}}, \quad (13)$$

where $\psi = \tilde{\beta}(|g|^2 - 2\tilde{R}_{\mathrm{n}}\Re\{\tilde{\rho}^* g\} + \tilde{R}_{\mathrm{n}}^2)$. The complex conjugate operation is denoted by $(.)^*$, while $\Re\{.\}$ denotes the real part of the input argument.

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