A Cooperative Massive MIMO System for Future In-Vivo Nano-Networks

Widad Belaoura, Khalida Ghanem, Muhammad A. Imran, Akram Almainy, and Qammer H. Abbasi

***Abstract*—Terahertz (THz) propagation inside human body tissues suffers from a low achievable capacity which drastically limits the usefulness of in-vivo nano-scale networks. In this paper, a virtual massive multiple-input-multiple-output (m-MIMO) array architecture constructed by the cooperative and opportunistic action of distributed nano nodes to form a cluster, is introduced for the first time for in-vivo nano communications. Moreover, a joint carefully designed scheme merging an antennas selection based-maximum magnitude (MM) criteria and spatial modulation (SM) transmission concept, is incorporated within this virtual m-MIMO architecture, as a way to achieve the best compromise between performance and complexity. The capacity maximization achieved by the proposed MM antennas selection is also derived for the proposed system. Simulation results consolidates the effectiveness of the proposed MM antenna selection assisted SM for virtual m-MIMO system inside human bodies. It is shown that the MM-antenna selection can greatly improve the performance of the proposed architecture in terms of bit error rate (BER) and reduce the complexity.**

***Index Terms*—Terahertz (THz) band, In-vivo nano communication, massive MIMO, Spatial modulation, nano scale.**

I. Introduction

Terahertz (THz) communication is considered as an emerging technology to support an extremely high data rate and a superior network capacity in the upcoming sixth generation (6G) of wireless communications [1]. Exploiting the huge available bandwidths of the THz band between 0.03 THz and 10 THz is envisioned as a viable solution that would ensure better effectiveness in medical diagnosis and treatments for advancing healthcare and biomedical applications. However, nano networks span not only the biomedical field for bio-hybrid implants [2], [3], non-invasive surgery [4], [5], and tissue engineering [6], [7], but also environmental purposes for bio control [8], [9] and bio-degradation assesments [10], industriel objectives for product quality control, and military ones for nuclear, biological and chemical defences [11].

In biomedical field, body-centric nano networks mostly target intra-body health monitoring, and the design of drug delivery and artificial immune systems [12], [13] with the aim of ensuring the continuous and comfortable monitoring of the patients' vital parameters. This technology has recently attracted a substantial research interest, due to its ability to reach small and delicate body sites easily. The incorporation of the nano devices within the body would not have been envisaged without the evolution of new materials such as graphene and carbone nano tubes, which will enable the efficient radiation of the THz electromagnetic-waves through the human tissues [14], [15].

In-vivo nano-machines can exchange information through four mechanisms, namely molecular (MC) [16], [17], electromagnetic (EM) wave [18], [10], [19], acoustic [20] and nanomechanical communications. The great part of the current studies are carried out solely on the two former types of communications. However, it appears that one of the impeding limitations of the molecular communications lies in their low achievable data rate, which drastically limits their usage in nanosensor networks. In this context, EM waves-based nano communications become a more interesting approach, aided by the fact that biological tissues are not ionized at THz frequencies [21].

One of the major concerns narrowing the scope of the application of the in-vivo communications at the THz band is their inherent characteristics encompassing the huge propagation losses and the molecular absorption noise, which limits the required communication distance between the nano-nodes for an acceptable operation quality [22], [23]. Basically, finding a practical solution to face these channel adverse conditions will require a careful design of these communication systems. On the other hand, the THz band offers an opportunity for ensuring the lacking frequency resources and meeting the exploding capacity demands on wireless networks, thanks to the offered ultra bandwidth. Furthermore, because of the corresponding very short wavelength, the packaging of a great number of nano devices is made possible in a smaller area [24]. However, deploying conventional massive multiple-input multiple-output (m-MIMO) antennas for such wireless sensor nodes might not be realistic inside human bodies. Rather, it seems that a more interesting design of nano scale communications can take the shape of virtual MIMO implemented via cooperative techniques, as reported in [25], [26].

However, one of the main impediments to the practical deployment of large scale MIMO systems resides in the requirement of one radio frequency (RF) chain per each used antenna, which can rapidly lead to a hardware prohibitive complexity, in addition to a considerable amount of power consumption. In this perspective, spatial modulation (SM) technique has been proposed as an attractive low complexity solution and has drawn a great deal of attention from experts, due to its powerful performance enhancing, coverage increas-

Widad Belaoura is with Electrical Engineering Department, Ecole Nationale Polytechnique, Algiers, Algeria (widad.belaoura@g.enp.edu.dz).

Khalida Ghanem is with the Advanced Technologies Center, Algiers, Algeria (kghanem@cdta.dz).

Muhammad Ali Imran and Qammer Hussain Abbasi are with the James watt school of engineering, University of Glasgow, Glasgow, UK ({muhammad.imran, qammer.abbasi}@glasgow.ac.uk).

Akram Alomainy is with the School of Electronic Engineering and Computer Science (EECS), Queen Mary University of London, Mile End Road, London, E1 4NS, UK (a.alomainy@qmul.ac.uk).

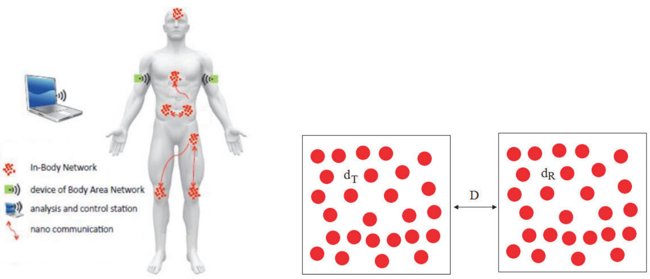

Fig. 1. Cooperative clusters in-vivo nano network.

ing and complexity reducing capabilities. To achieve this, in conventional SM, one of the available transmit antennas is solely activated to convey extra spatial information in addition to the data symbols [27], [28], [29]. In this scheme, the conventional signal, for instance of dimension 2D such as in quadrature amplitude modulation (QAM), is extended to a 3D signal by superimposing the antenna-index to the classical M-ary signal. In conventional m-MIMO architectures, the receiver could apply the maximum likelihood (ML) optimum detector, which is computationally prohibitive when the number of transmit antennas becomes large. In this context, SM becomes quite attractive because of the activation of a unique transmit antenna, which involves the using of a single RF chain at the transmit side. This also implies the sole retrieval of index of the antenna which has been activated, and the recovery of the data emanating from this latter, through simple linear techniques, such as zero forcing (ZF), or i-maximum ratio combining (i-MRC) [30], [31].

In the current state of the art, there have been few reported studies on THz communications adopting MIMO technology [22], [24], [32], [33], [34], including the ones which have carried out an initial investigation on in-vivo communications. In [32] the authors have proposed the use of graphene antenna-based reconfigurable MIMO systems for (1-10) THz communications. The work in [24] has introduced the concept of ultra-massive MIMO communications for THz-band as a way to increase the communication range and the achievable capacity. Moreover, the authors in [33] analysed the performance of a 2×2 in-vivo MIMO system relative to a single input-single output (SISO) counterpart, in terms of bit-error-rate (BER) performance. The study in [22] has proved that not only MIMO in-vivo nano networks can achieve a superior performance compared to SISO alternatives, but also achieve a considerably better capacity when the receiver (Rx) antennas are placed at the side of the human body. The authors in [34] have investigated the achievable channel capacity when spatial diversity is incorporated in body-centric THz nano networks. To the best of authors' knowledge, cooperative m-MIMO architectures relying on distributed antennas for in-vivo nano-scale communications at the THz frequency band, and the joint SM technique and magnitude maximization (MM) antennas selection has not been presented yet.

A. Contributions

The main contributions of this paper are summarized as follows:

- The first contribution of this work is the introduction of a novel networking architecture, evolving around the incorporation of spatially-distributed cooperative m-MIMO nodes for in-vivo nano communications, where the cluster of these nodes form a virtual m-MIMO nano scale network which sees its capacity enhanced through the nodes collaboration.
- The second contribution concerns the computational complexity pertaining to m-MIMO and which can not be afforded with nano in-body architectures. Indeed, this complexity which increases exponentially with the number of antennas is overcome via the adoption of the SM technique. Furthermore, a new appropriate antenna selection approach is applied in the m-MIMO architecture to further improve the achievable capacity. The idea of antennas selection is based on the criterion of MM, where the best transmit antennas subset which provides the highest in-vivo channel gain among all available transmit antennas is selected, and afterwards the SM transmission is performed only on the antennas in the subset. We show that the combination of MM-antennas selection and SM reduces significantly the system and computational complexities and leads to a better performance of virtual m-MIMO system in terms BER and spectral efficiency.

The remainder of this paper is organized as follows. The proposed MM-SM-virtual m-MIMO nano scale system model is introduced in Section II. In Section III, the involved in-vivo channel characteristics are depicted, followed by the description of the proposed communication scheme in Section IV. Numerical results and their discussions are presented in Section V, and conclusions are drawn in Section VI.

II. Proposed System Model

We consider a virtual m-MIMO system, with N_t nano transmitters (Tx) and N_r nano receivers (Rx), both uniformly distributed within a very small area inside a human body, with a Tx-Rx separation distance of D, as shown in Fig. 1. The closest nano nodes in the transmit cluster are connected to a central unit (CU), which performs the required processing. The proposed processing approach comprises of two major steps: one aiming at reducing the size of the channel matrix, hence the hardware complexity, while the second concerns the SM operation. In the first stage, the N_{A} among N_t transmit antennas yielding the highest quality of communication per receive element are retained. Indeed it has been observed that the channel experiences a sparsity in the spatial domain, which means that for a given receive antenna, only few transmit antennas are significantly contributing in the generation of the signal at its level because of the higher link magnitude. The indices of the retained transmit antennas for all receive elements are then padded to form a set of N_{SM} cardinality, thus giving birth to a new channel matrix of size $N_{\text{SM}} \times N_r$. This is confimed by the representation of the system in Fig. 2, where it is shown that the receiver selects N_{SM} antennas according to

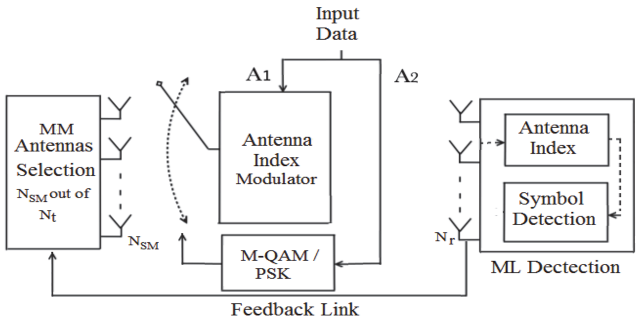

Fig. 2. Antennas selection aided spatial modulation system model for in-vivo nano-scale communication.

the specific MM selection criterion, which the corresponding indices are sent to the transmitter through a feedback link. This selection procedure will be depicted later in Section III. Consequently, the new channel matrix $\mathbf{H}_s$ is used to form a new spatial constellation diagram for implementing the SM signal. Hence, according to the SM principle, if we denote M the order of the M-QAM modulation, the total bits per channel, which is given by $B = \log_2(N_{\text{SM}}) + \log_2(M)$, is divided into two sub-vectors of $\log_2(N_{\text{SM}})$ and $\log_2(M)$ bits, denoted by A_1 and A_2 respectively. The bits in A_1 are used to select a single antenna that will be activated to convey the modulated symbol generated by modulating the bit in A_2. The signal at the N_r receive antennas is given by:

$$\mathbf{y} = \mathbf{H}_s\mathbf{x} + \mathbf{w} \tag{1}$$

with $\mathbf{x} \in C^{N_{\text{SM}}\times 1}$ being the transmit vector expressed as,

$$\mathbf{x} = [0, ..., 0, s_m, 0, ..., 0] \tag{2}$$

where s_m is the m^{th} modulated symbol, which satisfies the unit-energy constraint $E[|s_m|^2] = 1$, $\forall m = 1, ..., M$, $\mathbf{H}_s$ is the $N_r \times N_{\text{SM}}$ in-vivo channel matrix, and $\mathbf{w}$ is the additive white Gaussian noise (AWGN) vector, whose elements are of zero mean and unit variance.

Due to the prior reduction of the channel matrix dimension through MM selection, ZF detector is made simpler despite being suboptimal, more particulary compared to the optimum ML detector. Furthermore, assuming that the channel state information (CSI) is known at the receiver side, the resulting signal after the application of the ZF processing is:

$$\hat{\mathbf{Z}} = \mathbf{H}_s^H\mathbf{y} \tag{3}$$

The corresponding transmit antenna index, needs to be estimated. This is done by finding the location of the element of the ZF output providing the maximum absolute value, which is described by the following equation:

$$\hat{\imath} = \arg \max_{\text{i}} |\hat{\mathbf{Z}}|, \quad i = 1, ..., N_{\text{SM}} \tag{4}$$

where $\hat{\imath}$ denotes the estimated value of the transmit antenna index. It follows that, the corresponding transmitted symbol could be retrieved as:

$$\hat{\text{q}} = Q(\hat{\mathbf{Z}}_{(i=\hat{\imath})}) \tag{5}$$

where $Q(.)$ refers to the constellation quantization function. If $\hat{\imath}$ and $\hat{\text{q}}$ are correctly estimated, the receiver can straightforwardly de-map the original transmitted information bits. It is readily seen that the computational complexity, in terms of real multiplications, which exponentially increases with N_r, N_t and/or M.

III. In-vivo nano scale Channel model

The in-vivo nano scale channel is considered as one of the most challenging mediums and has only recently come into focus again, due to the latest technical progresses in devices miniaturization, the developments witnessed in nanotechnology, and the affordable measurement campaigns of the pertaining channels carried out around the 1 THz band [15], [35]. Basically, the electromagnetic signal inside the human body at the THz frequencies travels through various dissimilar media that have different electrical properties, which leads to the degradation of the quality of the transmitted signal [36]. We have introduced a novel THz in-body channel model in [15] and validated it against the THz time-domain spectroscopy (THz TDS) skin measurements performed at Queen Mary University of London (QMUL). This channel model is extracted in terms of three characterizing parameters, namely the distance, the number of sweat ducts, and the frequency. Further details on these experiments are available in [15]. Accordingly, the inferred path-loss model between the j^{th} and the i^{th} nano nodes, could be expressed as:

$$\begin{aligned}\ell_{j,i} = &-0.2N + 3.98 + (0.44N + 98.48)d_{j,i}^{0.65} \\ &+ (0.068N + 2.4)f^{4.07}\end{aligned} \tag{6}$$

where N is the number of sweat ducts, f is the operating frequency in THz and $d_{j,i}$ is the euclidean distance between the nano nodes in millimiters (mm). The overall in-vivo channel model is then given as:

$$H_{j,i} = \frac{h_{j,i}}{\sqrt{\ell_{j,i}}} \tag{7}$$

where $h_{j,i} \sim CN(0, 1)$ is the small scale fading channel coefficient between the i^{th} transmit and j^{th} receive antennas. The spatially distributed links are used to construct a large cooperative MIMO system, of which the matrix is expressed as:

$$\mathbf{H} = \begin{bmatrix} H_{11} & H_{12} & \dots & H_{1N_t} \\ H_{21} & H_{22} & \dots & H_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ H_{N_r} & H_{N_r} & \dots & H_{N_rN_t} \end{bmatrix} \tag{8}$$

The quality of the wireless nano-network link is then evaluated in terms of signal to noise ratio (SNR), γ, as follows:

$$\gamma = \frac{P_s}{\sigma^2}\mathbf{H}\mathbf{H}^H \tag{9}$$

where the power of the m^{th} constellation symbol $P_s = 1$, and σ^2 is the variance of the AWGN at each j^{th}-i^{th} link. Assuming that equal power allocation scheme has been adopted at the transmitter, the corresponding achievable channel capacity of the resulting virtual MIMO system can be computed as:

$$C = \log_2\big(\det(\mathbf{I}_{N_r} + \boldsymbol{\gamma})\big) \tag{10}$$

IV. Proposed Antenna Selection aided Saptial Modulation technique

The evaluation of the characteristics of the in-vivo nano scale channel matrix $\mathbf{H}$, such as the achievable capacity in (10), could easily become computationally prohibitive with the increase number of transmit/receive antennas, which is the case in m-MIMO systems. Fortunately, the in-vivo THz channel is particularly characterized by poor coefficient nature owing to the high operating frequency, the complex propagation mechanisms inside the human body, and the lossy nature of the in-vivo medium, resulting in only few elements of the channel matrix holding dominant values at the reception side. Based on the above observations, the sparse nature of the in-vivo THz channel is exploited in this work, to propose a low complexity yet efficient antennas selection aided-SM scheme adapted for the virtual in-body m-MIMO system. Indeed, this architecture aims to reach a viable compromise between the maximization of the achievable capacity of the in-body system, and the reduction of computational complexity of the resulting approach. The key idea is to select a small set of transmit antennas from the N_t available ones, without inducing an obvious performance loss. To this end, the MM selection criteria is applied to search the best transmit antennas indices, corresponding to the ones with the largest magnitude per receive antenna [37]. Prior to that, the elements of the in-vivo channel matrix are sorted in descending order of magnitude and the sets of indices that yield the maximum power are searched, i.e:

$$T^{(j)} = \{i \in I(N_t) : |H_{i,j}|^2 \geq \xi^j \max_i |H_{i,j}|^2\} \tag{11}$$

where $I(N_t) = \{i - (N_t - 1)/2 : i = 0, 1, 2, ..., N_t - 1\}$ is a symmetric set of indices centered around 0, $T^{(j)}$ denotes the set of transmit antennas indexes with the strongest magnitude pertaining to the j^{th} receive antenna, with $j = 1, ..., N_r$ and $\xi^j \in [0, 1]$ is the threshold which is chosen independently for each receive antenna. Finally, the transmit antennas set of all selected antennas can be formed as [38]:

$$T = \bigcup_{j=1...J} T^{(j)} \tag{12}$$

It follows that the dimension of the channel will be reduced to:

$$\mathbf{H}_s = [:, H_s]_{s\in T} \tag{13}$$

where $N_r \times N_{\text{SM}}$ is the size of the new channel matrix $\mathbf{H}_s$, which depends on the number of dominant subsets $T^{(j)}$. From (10) we can see that the MM antennas selection leads to values of N_{SM} which change according to the channel distance. Based on the resulting channel matrix, the SM technique is then applied where only one antenna from $\mathbf{H}_s$ is activated to transmit the mapped APM symbol, while all other antennas remain inactive. The combination of the two schemes offers the features of low CSI feedback overhead and low computational complexity for the proposed virtual massive MIMO system. Indeed, the system SM-MIMO devoid of the antennas selection functionality requires $\log_2 N_t$ feedback bits which could become significant, especially for large N_t. Another advantage of using MM antennas selection is to maximize the channel capacity in the proposed system. This maximization which comes from capacity of virtual m-MIMO system could thus be given as:

$$\boldsymbol{C} = \text{arg max}\{\log_2\text{det}(\mathbf{I}_{N_r} + \frac{P_s}{\sigma^2 N_{\text{SM}}}\mathbf{H}_s\mathbf{H}_s^H)\} \tag{14}$$

where $\mathbf{I}_{N_r}$ is the $N_r \times N_r$ identity matrix, and $(.)^H$ represent the Hermitian Transpose of matrix. In the following **algorithm 1** is used to maximize the achievable capacity which ensures that the set of N_{SM} nano node on the in-vivo channel by selecting indices.

Algorithm 1 Maximization of capacity based-MM Antennas selection

Inputs: $\mathbf{H}_s$, N_{SM}, N_r, N_A, N_t.
Output: The achievable capacity.
Initialisation : index set $M^0 = \emptyset$

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for i= 1 : N_SM do
    Compute the maximum capacity C_i of the system with
    the channel matrix H_s by (14).
    Calculate the capacity C_{i+1} of the system.
    Compare the two values: if C_{i+1} > C_i, and find the
    maximum capacity should be selected.
    M_{i+1} <- M_{i+1} - T_i Otherwise it should be off.
    Set the optimum value of capacity is C_i.
    After the last iteration the highest capacity over all
    antennas are selected.
end for
The achievable maximum capacity C
```

V. Simulation Results

In this section, numerical results are provided to corroborate the performance of the proposed virtual m-MIMO system over the in-vivo THz channels and are obtained via 10^4 Monte Carlo simulations. The proposed system considered herein makes use of the effectiveness of the combination of antennas selection architecture and the SM scheme with ZF detector. Without loss of generality, 4-QAM modulation is adopted. For all these simulations, the system encompassing SM-based virtual m-MIMO architecture without antenna selection is taken as a benchmark. The system operates in the frequency band of 1 THz, and comprises $N_t = 128$ transmit antennas

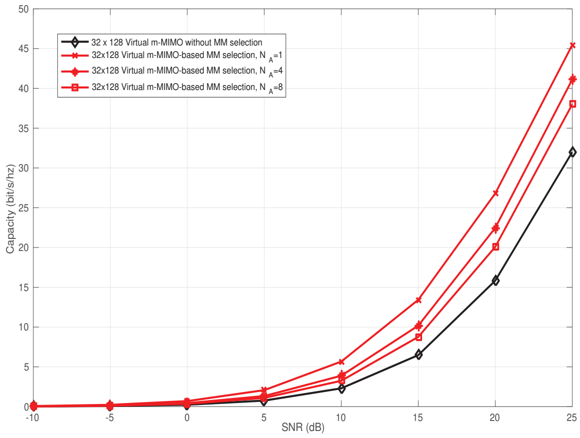

Fig. 3. Impact of the number of retained antennas per receiver on the channel capacity performance for virtual m-MIMO system based-MM selection.

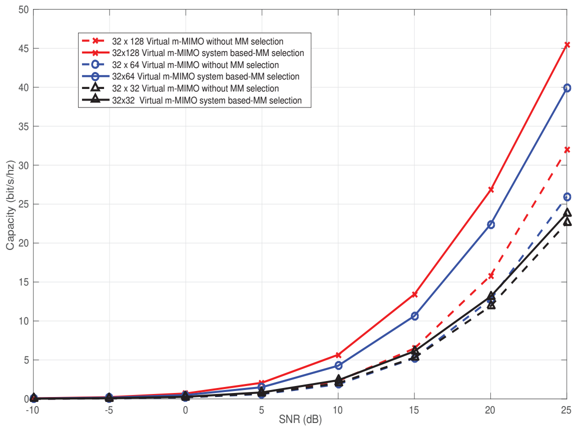

Fig. 4. Channel capacity for virtual m-MIMO system based MM selection with different configurations of transmit antennas.

and $N_r = 32$. Furthermore, it is assumed that the number of ducts in in-vivo channel is $N = 5$, the maximum transmission distance Tx-Rx is 0.3 mm, and the minimum distance between the nano nodes, either at the transmit or the receive side, is 0.001 mm.

In Fig. 3, the impact of the number of retained antennas per receive element in the MM selection method, namely N_A, on the achievable channel capacity for virtual m-MIMO architecture has been investigated. For this, the aforementioned antenna number was selected in the set $N_A = \{1, 4, 8\}$. From Fig. 3, it can be observed that the proposed MM-based solution yields a better capacity compared to m-MIMO-based counterpartwithout MM selection. This capacity gain is provided by the fact that MM solution activates an antenna among the ones yielding the highest SNR, hence resulting in a capacity gap between the two systems. Fig. 3 also shows that, when the SNR level is relatively high (more than 5 dB), for both antenna-distributed virtual MIMO, the proposed m-MIMO scheme based MM selection allows to achieve a higher data rate than the scheme without MM selection, even when the retained number of antennas through MM approach is 1.

Fig. 4 compares the attainable capacity between the previously investigated schemes for different transmit antennas configuration $N_t = \{32, 64, 128\}$, a number of received antennas fixed at $N_r = 32$ and one antenna $N_A = 1$ selected through MM processing. It can be seen from that figure that, increasing the number of transmit antennas, hence tending more and more to m-MIMO scenario, allows to significantly enhance the quality of the communication in the proposed antenna-distributed MM scheme over the alternative one. Indeed, in that context, using 64 transmit antennas in the former, allows to outperform the latter when equipped with 128 antennas. When the number of transmit antennas is low, i.e 32 antennas, opting for either one of the two schemes, yields approximately the same achievable capacity.

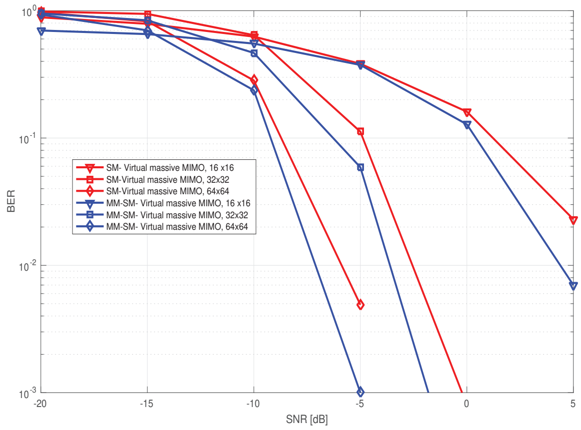

Fig. 5. BER performance comparison of SM-virtual m-MIMO system with and without MM selection.

Usually, the rate and the data reliability are conflicting objectives in the wireless system, and the gain in one aspect comes at the expense of a loss in the other one. Fig. 5 shows the BER performance of the MM aided SM for virtual m-MIMO proposal against SM-based one for different spatial configurations at the transceiver. It can be noted that increasing the number of receive antennas improves the performance of the ZF detection in both schemes. With the 64×64 MM-SM-based architecture, at an SNR level as low as -5 dB, the system offers a BER of 10^{-3}, hence enhancing the quality of the received data. This is a critical issue with such biomedical applications, where the transmission power of the signal should be as low as possible, and may even reach a level inferior to the one of ambient noise. Even with a 4×4 MIMO configuration, the proposed system is able to reach a BER value which is less than 10^{-2} at an SNR level of 5 dB, which is quite interesting.

In carrying out the simulations in Fig. 6 , the SM spectral efficiency η has been calculated shown in [30]:

$$\eta = \log_2(N_{\text{SM}}M)(1 + p_e\log_2 p_e + (1 - p_e)\log_2(1 - p_e)) \quad (15)$$

where p_e denotes the overall bit-error probability. Fig. 6 compares the spectral efficiency performance of our proposed system against the reference over the same in-vivo channels

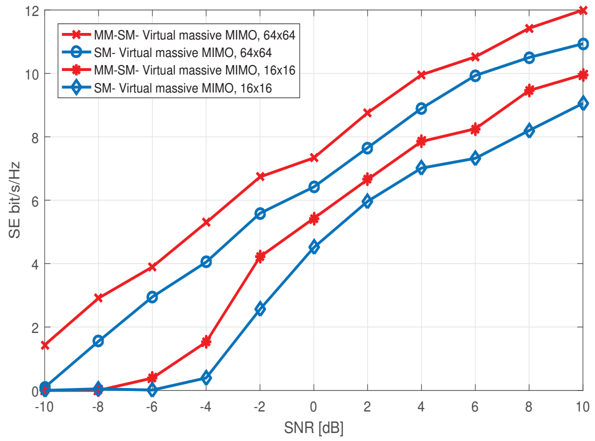

Fig. 6. Spectral efficiency performance comparison of SM-virtual m-MIMO system with and without antennas selection.

for different antenna configurations at the transceiver. From Fig. 6 it is noted that a slightly higher spectral efficiency is provided over SM solution, regardless of the SNR range.

VI. Conclusion

In this paper, a novel networking architecture for virtual m-MIMO exploiting distributed in-vivo wireless sensors to produce a nano scale communication enhancing the achievable capacity has been proposed. In addition, a design of a high-efficiency transmission scheme for in-vivo nano scale channels, which adopts a AS criteria to select the transmit antennas yielding the best channel conditions, among the available ones has been proposed. Afterwards, SM technique is applied on the resulting smaller subset of the channel matrix, thereby reducing the computational complexity of the whole system, and improving the offered capacity along with the data reliability, compared to SM-based virtual m-MIMO configuration. A better performance in terms of BER and more significant capacity are observed when increasing the order of the virtual m-MIMO channel matrix with AS-SM processing over the sole SM scheme. The results presented in this paper, shows the benefits of using AS-SM-Virtual m-MIMO antenna selection and SM technique for virtual m-MIMO architectures in in-vivo nano scale environments.

References

[1] F. Tariq, M. Khandaker, K.-K. Wong, M. Imran, M. Bennis, and M. Debbah, "A speculative study on 6g," *arXiv preprint arXiv:1902.06700*, 2019.

[2] K. Eric, *Nanosystems: molecular machinery, manufacturing, and computation*. Wiley, 1992.

[3] R. A. Freitas Jr, "What is nanomedicine?" *Nanomedicine: Nanotechnology, Biology and Medicine*, vol. 1, no. 1, pp. 2–9, 2005.

[4] K.-C. Kong, J. Cha, D. Jeon, and D.-i. D. Cho, "A rotational micro biopsy device for the capsule endoscope," in *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2005, pp. 1839–1843.

[5] S. Yim, E. Gultepe, D. H. Gracias, and M. Sitti, "Biopsy using a magnetic capsule endoscope carrying, releasing, and retrieving untethered microgrippers," *IEEE Transactions on Biomedical Engineering*, vol. 61, no. 2, pp. 513–521, 2013.

[6] S. Tasoglu, E. Diller, S. Guven, M. Sitti, and U. Demirci, "Untethered micro-robotic coding of three-dimensional material composition," *Nature communications*, vol. 5, no. 1, pp. 1–9, 2014.

[7] S. Kim, F. Qiu, S. Kim, A. Ghanbari, C. Moon, L. Zhang, B. J. Nelson, and H. Choi, "Fabrication and characterization of magnetic microrobots for three-dimensional cell culture and targeted transportation," *Advanced Materials*, vol. 25, no. 41, pp. 5863–5868, 2013.

[8] M. Heil and J. Ton, "Long-distance signalling in plant defence," *Trends in plant science*, vol. 13, no. 6, pp. 264–272, 2008.

[9] J. Han, J. Fu, and R. B. Schoch, "Molecular sieving using nanofilters: past, present and future," *Lab on a Chip*, vol. 8, no. 1, pp. 23–33, 2008.

[10] I. F. Akyildiz and J. M. Jornet, "Electromagnetic wireless nanosensor networks," *Nano Communication Networks*, vol. 1, no. 1, pp. 3–19, 2010.

[11] R. E. Smalley, *Carbon nanotubes: synthesis, structure, properties, and applications*. Springer Science & Business Media, 2003, vol. 80.

[12] P. Honeine, F. Mourad, M. Kallas, H. Snoussi, H. Amoud, and C. Francis, "Wireless sensor networks in biomedical: Body area networks," in *International Workshop on Systems, Signal Processing and their Applications, WOSSPA*. IEEE, 2011, pp. 388–391.

[13] T. Nakano, M. J. Moore, F. Wei, A. V. Vasilakos, and J. Shuai, "Molecular communication and networking: Opportunities and challenges," *IEEE transactions on nanobioscience*, vol. 11, no. 2, pp. 135–148, 2012.

[14] I. F. Akyildiz and J. M. Jornet, "Electromagnetic wireless nanosensor networks," *Nano Communication Networks*, vol. 1, no. 1, pp. 3–19, 2010.

[15] Q. H. Abbasi, H. El Sallabi, N. Chopra, K. Yang, K. A. Qaraqe, and A. Alomainy, "Terahertz channel characterization inside the human skin for nano-scale body-centric networks," *IEEE Transactions on Terahertz Science and Technology*, vol. 6, no. 3, pp. 427–434, 2016.

[16] B. Atakan, O. B. Akan, and S. Balasubramaniam, "Body area nanonetworks with molecular communications in nanomedicine," *IEEE Communications Magazine*, vol. 50, no. 1, pp. 28–34, 2012.

[17] K. Yang, "Characterisation of the in-vivo terahertz communication channel within the human body tissues for future nano-communication networks." Ph.D. dissertation, Queen Mary University of London, 2016.

[18] R. A. Freitas, *Nanomedicine, volume I: basic capabilities*. Landes Bioscience Georgetown, TX, 1999, vol. 1.

[19] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," *IEEE Transactions on Wireless Communications*, vol. 10, no. 10, pp. 3211–3221, 2011.

[20] T. Hogg and R. A. Freitas Jr, "Acoustic communication for medical nanorobots," *Nano Communication Networks*, vol. 3, no. 2, pp. 83–102, 2012.

[21] S. Balasubramaniam and J. Kangasharju, "Realizing the internet of nano things: challenges, solutions, and applications," *Computer*, vol. 46, no. 2, pp. 62–68, 2012.

[22] C. He, Y. Liu, T. P. Ketterl, G. E. Arrobo, and R. D. Gitlin, "Performance evaluation for mimo in vivo wban systems," *IEEE MTT-S International Microwave Workshop Series on in RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-Bio)*, pp. 1–3, 2014.

[23] K. Yang, "Characterisation of the in-vivo terahertz communication channel within the human body tissues for future nano-communication networks." Ph.D. dissertation, Queen Mary University of London, 2016.

[24] I. F. Akyildiz and J. M. Jornet, "Realizing ultra-massive mimo (1024× 1024) communication in the (0.06–10) terahertz band," *Nano Communication Networks*, vol. 8, pp. 46–54, 2016.

[25] A. Özgür, O. Lévêque, and D. Tse, "Spatial degrees of freedom of large distributed mimo systems and wireless ad hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. EPFL-ARTICLE-185421, pp. 202–214, 2013.

[26] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of mimo and cooperative mimo techniques in sensor networks," *IEEE Journal on selected areas in communications*, vol. 22, no. 6, pp. 1089–1098, 2004.

[27] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized mimo: Challenges, opportunities, and implementation," *Proceedings of the IEEE*, vol. 102, no. 1, pp. 56–103, 2014.

[28] M. Di Renzo, H. Haas, and P. M. Grant, "Spatial modulation for multiple-antenna wireless systems: A survey," *IEEE Communications Magazine*, vol. 49, no. 12, 2011.

[29] N. Serafimovski, A. Younis, R. Mesleh, P. Chambers, M. Di Renzo, C.-X. Wang, P. M. Grant, M. A. Beach, and H. Haas, "Practical implementation of spatial modulation," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 9, pp. 4511–4523, 2013.

[30] R. Mesleh, H. Haas, C. W. Ahn, and S. Yun, "Spatial modulation-a new low complexity spectral efficiency enhancing technique," in *2006 First*

International Conference on Communications and Networking in China. IEEE, 2006, pp. 1–5.

[31] P. Yang, Y. Xiao, Y. L. Guan, S. Li, and L. Hanzo, "Transmit antenna selection for multiple-input multiple-output spatial modulation systems," *IEEE Transactions on Communications*, vol. 64, no. 5, pp. 2035–2048, 2016.

[32] Z. Xu, X. Dong, and J. Bornemann, "Design of a reconfigurable mimo system for thz communications based on graphene antennas," *IEEE Transactions on Terahertz Science and Technology*, vol. 4, no. 5, pp. 609–617, 2014.

[33] C. He, Y. Liu, T. P. Ketterl, G. E. Arrobo, and R. D. Gitlin, "Mimo in vivo," in *Wireless and Microwave Technology Conference (WAMICON), 2014 IEEE 15th Annual*. IEEE, 2014, pp. 1–4.

[34] A. Abdelaziz, K. Yang, K. Qaraqe, J. Boutros, Q. H. Abbasi, and A. Alomainy, "Multiple antenna techniques for terahertz nano-bio communication," in *2018 IEEE 4th Middle East Conference on Biomedical Engineering (MECBME)*. IEEE, 2018, pp. 67–71.

[35] N. Chopra, A. Alomainy, and M. Philpot, "Investigating electromagnetic material properties of collagen at thz for health monitoring applications," in *Proceedings of the 5th EAI International Conference on Wireless Mobile Communication and Healthcare*. ICST (Institute for Computer Sciences, Social-Informatics, 2015, pp. 170–173.

[36] K. Yang, A. Pellegrini, M. O. Munoz, A. Brizzi, A. Alomainy, and Y. Hao, "Numerical analysis and characterization of thz propagation channel for body-centric nano-communications," *IEEE Transactions on Terahertz Science and technology*, vol. 5, no. 3, pp. 419–426, 2015.

[37] A. Sayeed and J. Brady, "Beamspace mimo for high-dimensional multiuser communication at millimeter-wave frequencies," in *2013 IEEE global communications conference (GLOBECOM)*. IEEE, 2013, pp. 3679–3684.

[38] P. V. Amadori and C. Masouros, "Low rf-complexity millimeter-wave beamspace-mimo systems by beam selection," *IEEE Transactions on Communications*, vol. 63, no. 6, pp. 2212–2223, 2015.