This is a postprint version of the following published document:

Sanchez-Fernandez, M., Tulino, A., Rajo-Iglesias, E., Llorca, J. & Armada, A. G. (2017). Blended Antenna Wearables for an Unconstrained Mobile Experience. *IEEE Communications Magazine*, 55(4), 160–168.

DOI: [10.1109/mcom.2017.1500722](https://doi.org/10.1109/mcom.2017.1500722)

© 2017, IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Blended Antenna Wearables for an Unconstrained Mobile Experience

Matilde Sánchez-Fernández, *Senior Member, IEEE*, Antonia Tulino, *Fellow, IEEE*, Eva Rajo-Iglesias, *Senior Member, IEEE*, Jaime Llorca, *Senior Member, IEEE*, Ana García Armada, *Senior Member, IEEE*

Abstract

We envision a world in which everyday life experiences can be augmented on-demand via the real time cloud processing of information sourced at multiple wireless end points. While current wireless systems focus their effort on improving the downlink capacity, these life-changing augmented experiences will only become a reality if the uplink capacity increases at the same or even higher rate. As a catalyzer for the capacity increase in both directions of the wireless communication link, we propose an innovative idea that brings the spectral and energy efficiency benefits of massive MIMO systems directly to the end user without compromising device size, weight, or power consumption. We propose a radio enhanced garment composed of blended textile antennas for seamless high data rate connectivity anytime, anywhere, addressing immediate and future needs. The real world applications for such a solution are tremendous, including enhanced connectivity in crowded spaces and remote areas, as well as symmetric extremely high data rates for access to next generation real-time services (e.g., augmented reality and cognition, real-time computer vision, telepresence, 3D video sharing) from ever lighter end user devices (e.g., Google Glass).

Index Terms

Wearables, massive MIMO, textile antenna technology

I. INTRODUCTION

In a fast approaching future, Internet traffic will be dominated by the consumption of resource and interaction intensive applications (e.g., augmented reality, real-time computer vision, immersive and interactive 3D video) running in distributed cloud nodes and accessed from a massive number of resource limited wireless user devices (e.g., smart phones/tablets/watches/glasses/wearables). The efficient and sustainable evolution towards this attractive future will call for disruptive innovations that ensure extremely high uplink and downlink data rates without affecting the desirable small size, lightness, and seamless properties of end user devices.

Next generation wireless communication system requirements are driven by these new bandwidth-intensive real-time applications. Fifth generation (5G) cellular networks envisages 100-fold capacity gains, simultaneous connections for billions of devices, and a 10 Gb/s individual user experience with extremely low latency and response times. It is obvious that no single technology will address all these challenges and that this radical change of performance will significantly modify the communication system at all levels [1].

In this work, with the aspiration of becoming one of the key enablers of the envisioned 5G 100-fold symmetric capacity growth, we propose a technology that directly addresses the needs of the most challenging and critical component of the communication system, the user end point. Any solution

This work has been partly funded by the Spanish Government through projects MIMOTEX (TEC2014-61776-EXP), CIES (RTC-2015-4213-7), ELISA (TEC2014-59255-C3-3R), and TEC2013-44019-R.

M. Sánchez-Fernández, E. Rajo-Iglesias and A. García Armada are with the Signal Theory & Communications Department, Universidad Carlos III de Madrid, Spain. E-mail: {mati,eva,agarcia}@tsc.uc3m.es.

A. M. Tulino is with the DIETI Department, University of Napoli, Federico II, 80138 Napoli, Italy.

A. M. Tulino and J. Llorca are with Nokia Bell Labs, Holmdel, NJ 07733, USA. E-mail: {a.tulino, jaime.llorca}@nokia-bell-labs.com.

that aims at boosting user devices' capabilities cannot compromise their seamless, lightweight, portable features. The deployment of a large number of antennas at the user end would be a candidate technological solution for improving the system capacity if we could go beyond the desirable reduced dimensions of the end device. Our approach exploits the user device's closest surroundings, i.e., the user's own clothing or accessories (e.g., laptop mats, bags, suitcases), to increase the device capabilities without compromising its lightweight, portability, and energy efficiency features. Specifically, we propose to deploy a large number of antennas at the user end, by blending textile antennas around the user's personal sphere (e.g., clothing, accessories). Such an antenna-based wearable would connect to any data-enabled user device, immediately boosting its communication capabilities. This technological solution, whose simulated performance, design alternatives, and feasibility are explored in detail in this work, shows very promising results in terms of achievable data rates. Fig. 1 shows that 40 textile antennas attached to a user device for uplink transmission can provide high data rate symmetric connectivity, enabling future wireless systems aligned with LTE-evolution demands. Observe that with today's available uplink bandwidth, a single-antenna terminal can only achieve data rates on the order of tens of Mb/s, enabling applications that would not go beyond current IP television (IPTV). Increasing the number of antennas at the user end enables services such as gaming, cloud computing, or even 3D high definition (HD) video, whose bandwidth needs move to the several hundreds of Mb/s.

This paper introduces MIMOMat, a disruptive blended antenna wearable technology with the potential of dramatically boosting mobile user experience. We provide a comprehensive overview of this breakthrough

Fig. 1. Average uplink throughput obtained via blended textile antennas at the user end for a bandwidth of 5MHz and 64 antennas at the base station in a realistic cellular scenario [2] (See also Sec. IV-D). The different applications that can be supported are highlighted based on [3].

technology that starts with a review of existing high capacity-achieving technologies (Section II) and then covers blended multi-antenna design (Section III-A), integration within the cellular infrastructure (Section III-B), spectral efficiency performance quantification (Section IV), and future challenges (Section V).

II. HIGH CAPACITY-ACHIEVING TECHNOLOGIES

There are three fundamental dimensions that can be explored for increasing the capacity of wireless communication systems: *i)* space (e.g., via network densification), *ii)* spectrum, and *iii)* spectral efficiency. A key enabling technology for high spectral efficiency is the use of multi-antenna systems, also known as MIMO [4]. This technology provides a radical increase in capacity that is proportional to the number of radiating elements. However, it is important to note that these gains are constrained by the smaller number of antennas deployed at any extreme of the communication system, up to the point that a system with two antennas at the transmitter and two antennas at the receiver outperforms a system with an extremely large number of antennas at the transmitter and just one antenna at the receiver [5]. The spectral efficiency gains that can be achieved via the deployment of a large number of antennas is hence limited by *i)* the inherent increase in signal processing complexity associated to MIMO systems [6], and *ii)* the spatial restrictions for the deployment of a large number of antennas at both ends of the communication link.

In a wireless cellular system, the base station (BS) can leverage a number of favorable attributes such as grid-power, signal processing capabilities, and physical space availability. However, the user end has become an obvious bottleneck for potential performance improvement: space restrictions usually apply, available power is highly limited, and non-costly hardware implementations are crucial. Recent studies have proposed the use of a massive number of antennas, also referred to as massive MIMO [6], at the BS. Massive MIMO at the BS can provide multiplicative total throughput gains by matching the number of users served to the number of antennas at the BS. However, the reduced number of antennas at the user end limits the per-user symmetric throughput required to enable next generation real-time applications. Indeed, in spite of massive MIMO advances at the BS, the tight restrictions at the user end become a major obstacle in LTE evolution. MIMOMat is a wearable extension to the user device with blended antennas in textile technology that aims at overcoming this hurdle by bringing massive MIMO also to the user terminal. This solution emerges as a disruptive joint venture between massive MIMO and textile antenna technologies that could provide on-demand symmetric data rate boosts unimaginable today.

The deployment of a large number of antennas in the least suitable component of the communication system is a challenging idea that leapfrogs current research in massive MIMO systems. To accomplish an end-to-end solution, not only the design and deployment of the antennas should be addressed, but also the signal processing needs, the RF chains design, and all hardware related issues that might jeopardize the wearability of the solution. We review these key aspects in the following sections.

III. SEAMLESS ANTENNA SYSTEMS

Textile antenna technology is sufficiently mature to be used in an application where the antennas need to be seamlessly embedded in the user's personal sphere. Indeed, recent studies have proposed the use of single textile antennas for off-body communications [7] and as a MIMO catalyst [8], [9]. However, to the best of our knowledge, textile antenna technology has not been proposed with a large deployment (tens of antennas) view, where open challenges related to radiated power, bandwidth, and the mutual coupling (MC) apply.

MIMOMat is the first technological solution that deploys a large antenna array, miniaturized in wearable form at the user end via embedded textile technology. Our design is intended to be a plug-&-play solution to which any data-enabled device can connect, providing on-demand high data rate, reliable, low power communications (see Fig. 2).

Fig. 2. System model. Example of a blended antenna wearable where the antennas are deployed in the back of a jacket.

A. Blended Antenna Wearable Design

We propose a tailored textile planar antenna array design as the enabling solution for providing the user terminal with a wearable extension comprising a large number of antennas. As described in [7], for an antenna to be wearable, it is necessary to combine the right selection of materials for both the conductive and the non-conductive components. With this in mind, we use a textile tissue (commonly felt) as a non-conductive substrate, while the metallization is implemented with electrotexile materials (e.g., Shieldit[®] conductive materials).

The planar antenna array solution was first simulated to design and fine tune the antenna parameters of interest, and later built to ensure its wearability, with special emphasis on weight and flexibility. The simulations were performed using *CST Microwave Studio*, a full wave simulation tool that provides radiation patterns (RP), antenna gains, and S -parameters (S stands for Scattering and such parameters are associated with return loss and Voltage Standing Wave Ratio). The S -parameters give crucial information about the antenna system performance: the antenna matching S_{ii} dictates the individual matching frequency and the bandwidth of the i -th antenna, while the S_{ij} parameter determines the MC between the i -th and the j -th antenna.

We designed squared patch antennas of length 46.5 mm using a 3 mm thick felt (with dielectric constant $\epsilon_r = 1.38$) as substrate. The simulations (see Fig. 3(a)) indicate that each individual antenna is well matched to a transmission center frequency of 2.5 GHz and exhibits a bandwidth of 70 MHz (defined as the range of frequencies for which the reflection coefficient S_{ii} is below or equal to -10 dB).

We remark that, while the proposed solution is designed with a central frequency of 2.5 GHz and a bandwidth of 70 MHz, both the antenna central frequency and the antenna bandwidth can be easily tuned for the specific application. It should be noted that different frequency bands are being explored for 5G, among which, the band below 6 GHz is intended to be used for LTE co-existence. In the proposed central frequency, the antenna design would approximately cover LTE band #7 if operating in FDD mode, or band #41 if operating in TDD mode [10].

For the planar array geometry, we chose an 80 mm inter-element distance (0.66λ) to minimize the MC among antennas, and deployed the squared patch antennas following $M_h = 5$ columns in the horizontal plane and $M_v = 8$ antenna rows in the vertical plane (see Fig. 3(b)). The total planar array size is $M = M_v \times M_h = 40$ antennas occupying 44.6×60.6 cm². Such a planar antenna array could be deployed for instance in the back of a jacket, as shown in Fig. 2, or in a flexible and lightweight textile mat that could easily fit in a bag. When jointly deploying the antennas in a planar array, the RPs of the individual antennas slightly vary (see the different RP shapes in Fig. 3(b)) with antenna gains going from 7.58 to 8.05 dB depending on the relative position of the antennas. It is important to note that the radiation to

Fig. 3. Textile antenna planar array simulated performance: (a) S -parameter magnitude values for antenna placed approximately in the center of the planar array. The antenna matching is given S_{ii} and also the mutual coupling with the four antennas surrounding up, down, left, right (S_{ij}); (b) Deployed antenna set and example of radiation pattern.

the body is minimum, as clearly shown in Fig. 3(b) with negligible radiation below the planar array. In addition, the simulated MC among antennas, determined by the S_{ij} parameters, is always below -20 dB (see Fig. 3(a)).

Finally, the antennas were built with the same materials and geometry chosen in the CST simulation stage. The actual deployment confirmed the light-weight properties of the solution, with 3 grams per antenna, and the high flexibility provided by the felt and the electrotexile material.

B. Blended Antenna Wearables in Next Generation Cellular Networks

The integration of MIMOMat into a cellular infrastructure can be devised in Fig. 2. Here, the blended antenna wearable relies on two important interfaces: one interface between the user device and the blended antenna wearable (a jacket in Fig. 2), and a second interface between the wearable and the cellular network.

The first interface connects a data enabled device (e.g., phone/tablet/watch) with the massive MIMO blended antenna wearable. The device-wearable interface should support the high data rates envisioned to be delivered via the MIMOMat. A feasible wired interface, in terms of connection rates, would be based in USB 3.1 with a transmission rate of 10 Gb/s. The wireless HD technology interface (WiHD), designed to enable wireless streaming of high-definition multimedia between source devices and displays, could be a second option. The link rate supported by this technology is 1 Gb/s. Both technologies have their pros and cons and the interface choice should also take into account the complexity burden (in terms of specific hardware and signal processing requirements) on the wearable implementation.

The second interface connects the massive antenna wearable to the wireless network and it is the foundation for the capacity boost experienced by the end user. This interface needs to define a novel physical layer (PHY) that will eventually override the original physical layer of the user device. This PHY layer should specify duplexing schemes for uplink-downlink communication, synchronization, channel estimation, signal processing, and all the required signaling to be compliant with the BS PHY. The associated electronics and powering components included in the wearable should feature lightweight, flexibility, and low power consumption requirements [11]. The rest of the communication protocols (over PHY) shall be supported by the device that is connected to the wearable extension.

In summary, the MIMOMat, with existing wireless/wired interfaces to connect to the user device, and novel PHY protocols to connect to the wireless network, becomes a plug-&-play solution to which any data-enabled device can connect in order to enhance its connectivity and data throughput.

In the following section, we assess the potential impact of MIMOMat on users' mobile experience by identifying the tradeoff between the complexity burden of PHY functionality on the wearability of the MIMOMat and the achievable data rates.

IV. UNCONSTRAINED MOBILE EXPERIENCE

Today's wireless data traffic is dominated by multimedia content delivery services such as on-demand audio and video streaming, which require high data rates in the downlink. The uplink capacity is limited, not only because of the technological constraints (e.g., size, power, computational complexity) inherent to the mobile equipment already mentioned in previous sections, but also because most of current and historical data communication services have not demanded high bandwidth requirements in this direction. Asymmetric capacity assumptions between downlink and uplink have therefore largely characterized the design and implementation of wireless communication systems. Blended antennas wearables are envisioned to break this tendency and become one of the key 5G enablers (See Fig. 1) providing reliable symmetric high data rates to/from any user device.

Think of a user trying to enjoy an augmented reality application from a lightweight video-enabled device. The reduced uplink data rate limits the service to 2D video with a few augmented tags that identify a subset of objects in the captured scene. As soon as the user connects the device to his MIMO-enabled wearable, the application delivers 3D video with real-time full scene analysis, a dramatic and instantaneous user experience boost.

In this section, in order to quantify the disruptive performance improvements that can be achieved via MIMOMat, we focus on two simulated scenarios: 1) an idealistic scenario with a single user equipped with a MIMOMat transmitting to a BS, and 2) a realistic cellular network scenario with the presence of multiple interfering users. For both scenarios, we evaluate the average achievable uplink rates. To this end, we first describe the channel model and the possible transmission strategies, and then quantify the achievable data rates for each of the two scenarios.

A. Channel model and parametrization

The narrowband massive MIMO channel is described by a $N \times M$ channel matrix $\mathbf{H}$. The channel matrix is characterized by the antenna array geometry, radiation patterns in transmission and reception, and the surrounding scattering environment. The element h_{nm} in the channel matrix $\mathbf{H}$ is described by the Green's function [12] sampled at the position of the n -th receiving antenna $\mathbf{r}'_n$ given that the point source is located at the m -th transmitting antenna ($\mathbf{r}_m$):

$$h_{nm} = \int \int \mathcal{G}_m(\theta, \phi) \mathcal{G}'_n(\theta', \phi') S(\mathbf{k}'(\theta', \phi'), \mathbf{k}(\theta, \phi)) e^{-j\mathbf{k}(\theta, \phi)\mathbf{r}_m} e^{j\mathbf{k}'(\theta', \phi')\mathbf{r}'_n} d\mathbf{k}'(\theta', \phi') d\mathbf{k}(\theta, \phi). \quad (1)$$

In (1), $\mathcal{G}_m(\theta, \phi)$ and $\mathcal{G}'_n(\theta', \phi')$ are the radiation patterns in azimuth (ϕ) and elevation (θ) at the transmitter and receiver, respectively, $\mathbf{k}(\theta, \phi)$ and $\mathbf{k}'(\theta', \phi')$ represent the wave vector space at the transmitter and receiver, respectively, and $S(\mathbf{k}'(\theta', \phi'), \mathbf{k}(\theta, \phi))$ is the channel scattering function, which relates the plane wave's emitting and receiving directions, $\mathbf{k}$ and $\mathbf{k}'$, respectively. It should be noted that there is no dependence on time of the position of the antennas, $\mathbf{r}'_n$ and $\mathbf{r}_m$, and hence we are considering a static scenario with no block or relative movement of the antennas.

In order to quantify the achievable rates for the two described scenarios, the channel model in (1) needs to be parametrized with the antenna design parameters obtained in Section III. Accordingly, the simulated RPs of the wearable antennas are used for $\mathcal{G}_m(\theta, \phi)$, and the proposed planar array geometry with 0.66λ separation is used for the antenna positions $\mathbf{r}_m$. Recall that the proposed design contains $M = 40$ antennas. However, in order to highlight the benefits of this massive $M = 40$ antenna deployment, we also consider planar arrays with less number of antennas, $M = \{1, 5, 10, 20, 40\}$, all with inter-element distance of 0.66λ and with their corresponding measured RPs. In terms of mutual coupling, while all measured MC values were below -20 dB and could be easily neglected, we still include them in our simulations. For the sake of simplicity, we consider ideal antennas (broadside RP) with zero mutual coupling at the BS (receiving end), i.e., $\mathcal{G}'_n(\theta', \phi') = 1 \forall \phi, \theta$ values. The BS deploys $N = \{1, 4, 8, 64\}$ antennas in a linear

array with a distance among antennas of $\lambda/2$, except for $N = 64$ where we assume a 8×8 planar array with the same inter-element separation, providing the receiving antenna positions $\mathbf{r}'_n$.

For the scattering function parametrization $S(\mathbf{k}'(\theta', \phi'), \mathbf{k}(\theta, \phi))$, we follow standard approaches in literature. At the user end, we assume full angular dispersion that we shall model uniformly. At the BS, the angular spread could be significantly smaller than at the user end, depending on the position of the base station. In order to get a worst case performance, we assume narrow angular spread in azimuth (≈ 30 degrees) and negligible angular spread in elevation.

With all these parameters, channel matrix samples can be generated and used for rate computations. It should be noted that we are not only taking into account the positive increase in the matrix dimension that is generated by the fact that we add more antennas at the user end, but we are also considering the antennas' non-ideal characteristics or impairments such as non-broadside RP, mutual coupling, and antenna gains.

B. Transmission strategies in the wearable

As stated in Section III-B, the signal processing functionality at the MIMOMat is a key component driving the fundamental complexity-performance tradeoff. In the case of a massive antenna wearable designed to boost symmetric data rates, the signal processing complexity is dominated by *i*) the precoder computational complexity (e.g., matrix operations, finite precision operations) and *ii*) the amount of channel state information (CSI) available at the MIMOMat.

We propose four different precoders, each of them characterized by different computational complexity and available CSI at the transmitter:

- *Optimal precoder under instantaneous CSI (Optimal I-CSI)*: the precoder instantaneously diagonalizes the channel matrix and its squared singular values are given by the optimal water-filling (WF) power allocation [2].
- *Matched filter (MF)*: the precoder consists of the transpose conjugate of the channel matrix [2].
- *Optimal precoder under statistical CSI (Optimal S-CSI)*: the precoder's eigenvectors diagonalize the channel matrix in an average manner, while its squared singular values are equal to the fraction of average signal power recovered by a minimum mean squared error (MMSE) receiver from the corresponding eigenvectors [13].
- *Optimal precoder with no CSI (No CSI)*: the precoder is isotropic, i.e., equal to the identity matrix [2].

Note that the first two precoders require the transmitter to accurately track the instantaneous CSI, which may be feasible with the system working in Time Division Duplexing (TDD) mode, while Optimal S-CSI only requires access to the channel distribution, with less sensitivity to the channel coherence time, and No-CSI does not require any knowledge. In terms of computational complexity, *Optimal I-CSI* requires a matrix decomposition computation at any channel use, while *Optimal S-CSI* only performs such computation at any change of the channel statistics. Note that MF and No-CSI directly use the transport conjugate of the channel matrix and the identity matrix, respectively, and hence, do not require any extra computation.

C. Uplink Achievable rates in an idealistic scenario

In this section, we assess the throughput performance of an idealistic scenario where a single wireless device equipped with a MIMOMat transmits to a BS over a channel described as in Section IV-A. Specifically, we focus on quantifying the average achievable uplink rate (in bits/s/Hz), which for Gaussian input signal¹ is given by

$$R = \mathbb{E} \left[\log \det \left(\mathbf{I}_N + \frac{\text{SNR}}{\text{Tr}\{\mathbf{Q}\}} \mathbf{H} \mathbf{Q} \mathbf{H}^\dagger \right) \right], \quad (2)$$

¹We remark that under more practical signaling schemes (non-Gaussian signaling), there will only be a loss of approximately 3 dB.

Fig. 4. Average achievable rates in the uplink in an idealistic scenario: (a) Performance trade-off for different number of blended antennas deployed at the wearable $M = \{1, 10, 20, 40\}$. The BS antenna configuration is fixed to $N = 4$ representing a nowadays scenario; (b) Performance trade-off for $M = 40$ blended antennas deployed at the wearable. The BS allows different antenna configuration $N = \{1, 4, 8, 64\}$ representing the evolution of BS in future wireless systems.

where SNR denotes the transmitting Signal-to-Noise ratio, $\mathbf{I}_N$ is the $N \times N$ identity matrix, $\mathbf{H}$ is the narrow band MIMO $N \times M$ channel matrix, as described in Section IV-A, $\mathbf{Q}$ denotes the input covariance matrix chosen depending on the implemented precoding strategy, and the expectation is taken over the channel distribution. Finally, note that when the achievable rates are simulated for a specific signaling bandwidth W , as in some of the scenarios studied here, the throughput is then given by $W \times R$, and measured in bits/s.

In the following, we plot the average achievable rates as given by (2), for the four transmission strategies detailed in Section IV-B, each corresponding to a different $\mathbf{Q}$. Under the assumption of instantaneous CSI at the transmitter, the input covariance matrix takes the form of $\mathbf{Q} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^\dagger$, where $\mathbf{U}$ are the eigenvectors of $\mathbf{H}^\dagger\mathbf{H}$, while $\mathbf{\Lambda}$ is the result of the classical WF power allocation algorithm. Under MF precoding, the input covariance matrix takes the form $\mathbf{Q} = \mathbf{H}^\dagger\mathbf{H}$. In the statistical CSI scenario, the eigenvectors of $\mathbf{Q}$ are given by the eigenvectors of the channel covariance matrix $\mathbb{E}[\mathbf{H}^\dagger\mathbf{H}]$, while its eigenvalues are obtained via the optimal power allocation algorithm described in [13]. Finally, if no CSI is available at the transmitter, $\mathbf{Q} = \frac{1}{M}\mathbf{I}^2$.

In this context, we analyze two different scenarios with varying number of antennas at both ends of the communication system. In the first scenario, motivated by the limited number of antennas in today's BS, we consider $N = 4$ antennas at the BS and $M = \{1, 10, 20, 40\}$ blended antennas at the user. Note that in this case, the potential linear increase of the transmission rate with the number of antennas at the wearable will be limited by the 4 antennas at the BS. Fig. 4(a) shows that the deployment of an increasing number of blended antennas at the user end has clear benefits in terms of achievable data rates. In this case, the plots show a linear increase of spectral efficiency with $\log$ SNR. For a given precoding strategy, the gain can be seen in terms of the spectral efficiency for a fixed SNR, or in terms of SNR for a target achievable rate. Compared to just one antenna, the deployment of 40 blended antennas at SNR = 5 dB gives an increase of up to $4\times$ in achievable data rate.

In the second scenario, in order to illustrate the multiplicative gains with the number of antennas, we consider large antenna deployments also at the BS, with $N = \{1, 4, 8, 64\}$. In this case, the performance of the different precoding strategies is shown in Fig. 4(b) under the assumption of $M = 40$ blended antennas at the user. Note that in this case, going from 4 to 64 antennas at the BS, we achieve a gain of up to $14\times$ in spectral efficiency, confirming the expected multiplicative antenna gains.

²Note that all the transmission strategies are capacity achieving, except the MF precoding. This is why we use the term achievable rate, instead of capacity, throughout the document.

Fig. 5. Percentile of users achieving a certain uplink throughput with a signaling bandwidth of 5MHz in a realistic cellular scenario [2] when the number of textile antennas range $M = \{1, 5, 10, 20, 40\}$: (a) Base station with an antenna deployment of $N = 64$; (b) Base station with an antenna deployment of $N = 4$.

Both Figs. 4(a) and 4(b) clearly show that, in all the simulated regimes, *Optimal S-CSI* and *No CSI* differ in at most 1 bit/s/Hz or 1 dB of SNR. The reason is that, due to the low mutual coupling of the antenna design described in Section III-A, the elements of the channel matrix are very low correlated, i.e., $\mathbb{E}[\mathbf{H}^\dagger \mathbf{H}] \approx \mathbf{I}_M$. It is worth emphasizing that the low correlation across the channel matrix elements achieved thanks to the careful antenna design, is a highly desirable feature that allows the MIMOmat-enabled device to fully exploit the multiplicative antenna gains of massive MIMO systems. Note that the performance can be further improved if in the MIMOmat design we allow higher complexity to exploit more accurate CSI. Specifically, assuming perfect instantaneous CSI, either *MF* or *Optimal I-CSI* precoders could be implemented. Observe that the difference in performance between *MF* and *Optimal I-CSI* is small, suggesting that *MF* represents a good compromise between performance and complexity.

D. Working in realistic interference cellular scenarios

In order to assess the performance of MIMOmat in a realistic SNR scenario, we now simulate the average uplink achievable throughput in a cellular network with a transmission bandwidth of 5 MHz, in the presence of other interfering users. In the simulations, we assume uniform user distribution and a network consisting of 19 3-sector base stations with N antennas per sector, serving one user per sector at any time-frequency slot. Users get assigned to the BS with least propagation loss [2]. The communication scheme works in TDD mode. In these systems, channel reciprocity can be used to train on reverse link and obtain an estimate of the channel at the transmitter (base station or user depending on whether downlink or uplink is considered). Specifically, here we assume an uplink consisting of two phases: uplink training and data transmission. The uplink training phase consists of users transmitting training pilots, and base stations obtaining channel estimates. In order to characterize the achievable rates under imperfect channel estimation and pilot contamination, we follow the approach of [14], [15], which assume a MMSE estimator for the channel matrix and provide a lower bound on the achievable rate. According to simulations that are not shown here due to space limitations, the trends in Figs. 4(a)-4(b) still hold in this interference scenario with imperfect CSI, with the MF precoder yielding the best compromise. As such, in this study we consider the MF precoder with the imperfect instantaneous CSI given by the MMSE estimator. Even though the designed antenna array in Section III may use a bandwidth of up to 70 – 80 MHz, here we choose a bandwidth of 5 MHz to show that even with today's cellular networks limited bandwidth, very high data rates can be achieved. In this study, we present the cumulative density function (CDF) of the throughput averaged over the fast fading channel realization as a function of the random user locations, for a given transmitted SNR.

In Figs. 5(a)-5(b), we provide the CDF of the achievable rates for $N = 4$ antennas at the BS (current deployment), and $N = 64$ (future deployment). Each user is assumed to be equipped with $M = \{1, 5, 10, 20, 40\}$ blended antennas. From these two scenarios we can observe dramatic gains as the number of blended antennas goes from 1 to 40 antennas. With an antenna deployment in the BS of $N = 64$ (see Fig. 5(a)), we can get up to $5\times$ in edge rate (covering 90% of the users), up to $6\times$ in median rate, and 470 Mb/s in peak rate (10% of the users) yielding a gain of $10\times$. Similarly, at a lower scale, with $N = 4$ antennas at the BS (see Fig. 5(b)), we can get up to $3\times$ in edge rate (covering 90% of the users), up to $4\times$ in median rate, and around 50 Mb/s in peak rate (10% of the users) yielding a gain of $4\times$.

V. FEASIBILITY OF A SEAMLESS LIGHTWEIGHT IMPLEMENTATION

Any technological gadget aimed at being seamlessly embedded into the user's personal sphere needs to have very strong requirements in terms of wearability. Ideally, we should move from something portable, where the user would notice that is carrying a new element, to a solution practically unnoticeable. In this case, the hardware design is key, and aspects such as powering, RF chain design, and the electronics would require further in-depth study. We next comment on each of these issues, detailing the different alternatives that we are currently taking into consideration as ongoing work.

A. Powering

How the antenna system and its associated signal processing components shall be powered is a strategic decision within the wearable solution design. In the case that the MIMOMat is connected to the user device via a wired interface, a straightforward powering solution is to use the batteries of the device itself. However, while the MIMOMat design is driven by low power requirements, this solution would inevitably lead to the need for additional batteries supplementing the terminal's own, in order to avoid quick battery depletions that would make the whole solution unusable. If the final powering solution is additional batteries, they should be light-weight, high capacity, and obviously rechargeable [11].

B. RF Chains Design

Conventional massive MIMO systems deploy a single or, at best, very few antennas at the user end [16]. Each antenna typically has one associated RF chain, which is one of the reasons why the number of antennas at the user end is very limited. Fig. 6 depicts a traditional multi-antenna design, illustrating the high level of hardware complexity. Clearly, one of the major challenges to make MIMOMat a reality is precisely the RF chains design, which also adds to the powering challenge previously mentioned.

C. Electronics

As an initial approach, and in order to provide a plug-&-play solution that overrides the device PHY layer, we would need to implement specific signal processing and PHY layer signaling in the MIMOMat. The required electronics are again constrained by space, power consumption, and wearability requirements. One alternative is to implement all the electronics in a unique board, detachable from the textile antenna gadget, that could be charged in a wall socket similarly to a conventional mobile/portable device. Less rigid alternatives are also available, such as the so-called *electronic textiles* that aim at being truly wearable [17], providing useful functionality, while discretely "disappearing" in the fabrics.

VI. CONCLUSIONS AND FUTURE WORK

The ultimate success of MIMOMat, a massive MIMO blended antenna wearable extension for the user device will strongly depend on its seamless usability and affordable cost. While, based on the preliminary design presented in this work, we are confident that MIMOMat will deliver remarkable gains in

Fig. 6. RF chains and processing board sketch.

symmetric data rates, important design aspects need to be addressed, especially those that may jeopardize the wearability, usability, and cost of the solution.

Our efforts are now focused on the hardware implementation, already highlighted in Section V, and other issues such as synchronization, duplexing schemes for uplink-downlink communication, channel estimation issues, and sensitivity of channel estimation to signal processing and physical layer signaling. In our view, excluding the hardware implementation, the remaining aspects do not appear critical under the design premises that we manage, and we are therefore confident that they will not significantly compromise the feasibility of our solution, as we expect to show in our future work.

REFERENCES

- [1] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta and P. Popovski, "Five disruptive technology directions for 5G", *IEEE Communications Magazine*, vol. 52, Feb. 2014, p.p. 74-80.
- [2] H. Huang, C. Papadias and S. Venkatesan, *MIMO Communication for Cellular Networks*, Springer New York, 2012.
- [3] GreenTouch Application Taxonomy Project, "GreenTouch Application Taxonomy", tech. report, GreenTouch, Feb. 2012.
- [4] Q. Li, G. Li, W. Lee, Moon-il Lee, D. Mazzarese, B. Clerckx, and Z. Li, "MIMO techniques in WiMAX and LTE: a feature overview", *IEEE Communications Magazine*, vol. 48, May 2010, p.p. 86-92.
- [5] C. Papadias, "On the spectral efficiency of space-time spreading schemes for multiple antenna CDMA systems", in *Thirty-Third Asilomar Conference on Signals, Systems, and Computers*, vol. 1, Oct. 1999, p.p. 639-643.
- [6] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors and F. Tufvesson, "Scaling Up MIMO: Opportunities and Challenges with Very Large Arrays", *IEEE Signal Processing Magazine*, vol. 30, Jan. 2013, p.p. 40-60.
- [7] P. Nepa and H. Rogier, "Wearable Antennas for Off-Body Radio Links at VHF and UHF Bands: Challenges, the state of the art, and future trends below 1 GHz", *IEEE Antennas and Propagation Magazine*, vol. 57, Oct. 2015, p.p. 30-52.
- [8] P. Van Torre, L. Vallozzi, C. Hertleer, H. Rogier, M. Moeneclaey and J. Verhaevert, "Indoor Off-Body Wireless MIMO Communication with Dual Polarized Textile Antennas", *IEEE Transactions on Antennas and Propagation*, vol. 59, Feb. 2011, p.p. 631-642.
- [9] Y. Ouyang, D. J. Love and W. J. Chappell, "Body-Worn Distributed MIMO System", *IEEE Transactions on Vehicular Technology*, vol. 58, May 2009, p.p. 1752-1765.
- [10] Radio Electronics, Resources, and Analysis for Electronic Engineers, "LTE frequency bands and spectrum allocations", <http://www.radio-electronics.com/info/cellular/telecomms/lte-long-term-evolution/lte-frequency-spectrum.php>, October 2016.
- [11] S. Xu, Y. Zhang et al., "Stretchable batteries with self-similar serpentine interconnects and integrated wireless recharging systems", *Nature Communications* 4, Feb. 2013.
- [12] D. Chizhik, "Slowing the time-fluctuating MIMO channel by beam forming", *IEEE Transactions on Wireless Communications*, vol. 3, Sept. 2004, p.p. 1554 - 1565.
- [13] A. Tulino, A. Lozano and S. Verdú, "Capacity-Achieving Input Covariance for Single-user Multi-Antenna Channels", *IEEE Transactions on Wireless Communications*, vol. 5, Mar. 2006, p.p. 662-671.

- [14] H. Huh, A. Tulino and G. Caire, "Network MIMO With Linear Zero-Forcing Beamforming: Large System Analysis, Impact of Channel Estimation, and Reduced-Complexity Scheduling", *IEEE Transactions on Information Theory*, vol. 58, Mar. 2012, p.p. 2911-2934.
- [15] J. Jose, A. Ashikhmin, T. Marzetta and S. Vishwanath, "Pilot Contamination and Precoding in Multi-Cell TDD Systems", *IEEE Transactions on Wireless Communications*, vol. 10, Mar. 2011, p.p. 2640-2651.
- [16] S. Wang, Y. Li, M. Zhao and J. Wang, "Energy-Efficient and Low-Complexity Uplink Transceiver for Massive Spatial Modulation MIMO", *IEEE Transactions on Vehicular Technology*, vol. 64, Oct. 2015, p.p. 4617-4632.
- [17] L. Buechley, M. Eisenberg, "The LilyPad Arduino: Toward Wearable Engineering for Everyone", *IEEE Pervasive Computing*, vol. 7, Apr. 2008, p.p. 12-15.

Matilde Sánchez-Fernández (SM'14) received the M.Sc. degree in telecommunications engineering and the Ph.D. degree from Universidad Politécnica de Madrid, Madrid, Spain, in 1996 and 2001, respectively. In 2000, she joined the Universidad Carlos III de Madrid, Madrid, where she has been an Associate Professor since 2009 teaching several undergraduate and graduate courses (M.Sc. and Ph.D.) related to communication theory and digital communications. Previously, she was a Telecommunication Engineer with Telefónica. She performed several research stays at the Information and Telecommunication Technology Center, The University of Kansas, Lawrence (1998), Bell Laboratories, Crawford Hill, NJ (2003 – 2006, 2015), Centre Tecnològic de Telecomunicacions de Catalunya, Barcelona, Spain (2007), and Princeton University, Princeton, NJ (2011). Her current research interests are signal processing for wireless communications, multiple-input multiple-output techniques, channel modeling in wireless communications and game theory and machine learning techniques applied to communications. In these fields, she has (co)authored more than 50 contributions to international journals and conferences.

Antonia M. Tulino (S '00 – M '03 – SM '05 – F '13) received the Ph.D. degree in Electrical Engineering from Seconda Università degli Studi di Napoli, Italy, in 1999. She held research positions at Princeton University, at the Center for Wireless Communications, Oulu, Finland and at Università degli Studi del Sannio, Benevento, Italy. From 2002 she has joined the Faculty of the Università degli Studi di Napoli "Federico II", and in 2009 she joined Bell Labs. From 2011, Dr. Tulino is Member of the Editorial Board of the *IEEE Transactions on Information Theory* and in 2013, she was elevated to IEEE Fellow. She has received several paper awards and among the others the 2009 Stephen O. Rice Prize in the Field of Communications Theory for the best paper published in the *IEEE TRANSACTION ON COMMUNICATION* in 2008. She has been principal investigator of several research projects sponsored by the European Union and the Italian National Council, and was selected by the National Academy of Engineering for the Frontiers of Engineering program in 2013. Her research interests lie in the area of communication systems approached with the complementary tools provided by signal processing, information theory and random matrix theory.

Eva Rajo-Iglesias (SM08) was born in Monforte de Lemos, Spain, in 1972. She received the M.Sc. degree in telecommunication engineering from the University of Vigo, Vigo, Spain, in 1996, and the Ph.D. degree in telecommunication engineering from the University Carlos III of Madrid, Madrid, Spain, in 2002. She was a Teaching Assistant with the University Carlos III of Madrid from 1997 to 2001. She joined the Polytechnic University of Cartagena, Cartagena, Spain, as a Teaching Assistant, in 2001. She joined the University Carlos III of Madrid as a Visiting Lecturer in 2002, where she has been an Associate Professor with the Department of Signal Theory and Communications since 2004. She visited the Chalmers University of Technology, Gothenburg, Sweden, as a Guest Researcher, from 2004 to 2008, where she has been an Affiliate Professor with the Antenna Group, Signals and Systems Department, since 2009. She has co-authored more than 50 papers in JCR international journals and more than 100 papers in international conferences. Her current research interests include microstrip patch antennas and arrays, metamaterials, artificial surfaces and periodic structures, gap waveguide technology, MIMO systems, and optimization methods applied to electromagnetism. Dr. Rajo-Iglesias was a recipient of the Loughborough Antennas and Propagation Conference Best Paper Award in 2007, the Best Poster Award in the field of metamaterial applications in antennas at the Metamaterials Conference in 2009, the Excellence Award to Young Research Staff at the University Carlos III of Madrid in 2014, and the Third Place Winner of the Bell Labs Prize in 2014. She is an Associate Editor of the *IEEE Antennas and Propagation Magazine* and the *IEEE Antennas and Wireless Propagation Letters*.

Jaime Llorca received the B.E. degree in Electrical Engineering from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 2001, and the M.S. and Ph.D. degrees in Electrical and Computer Engineering from the University of Maryland, College Park, MD, USA, in 2003 and 2008, respectively. He held a post-doctoral position at the Center for Networking of Infrastructure Sensors (CNIS), College Park, MD, USA, from 2008 to 2010. He joined Nokia Bell Labs at Holmdel, NJ, USA, in 2010, where he is currently a Research Scientist in the Network Algorithms Department. His research interests include energy efficient networks, distributed cloud networking, content distribution, resource allocation, network information theory, and network optimization. He is a recipient of the 2007 Best Paper Award at the IEEE International Conference on Sensors, Sensor Networks and Information Processing (ISSNIP), the 2016 Best Paper Award at the IEEE International Conference on Communications (ICC), and the 2015 Jimmy H.C. Lin Award for Innovation.

Ana García Armada (SM) received the Ph.D. degree in electrical engineering from the Polytechnical University of Madrid in February 1998. She is currently Full Professor at University Carlos III of Madrid, Spain, where she has occupied a variety of management positions. She is leading the Communications Research Group at this university. She has participated and coordinated several national and international research projects related to wireless communications. She is the co-author of eight book chapters on wireless communications and signal processing. She has published more than 100 papers in international journals and conference proceedings and she holds four patents. She has contributed to international organizations such as ITU and ETSI. She serves on the editorial boards of Physical Communication, IET Communications and IEEE Communications Letters. She has served on the TPC of more than 40 conferences. She has received a Young Researchers Excellence Award and an Award to Best Practices in Teaching, both from University Carlos III of Madrid. Her main interests are multi-carrier and multi-antenna techniques and signal processing applied to wireless communications.

Fig. 1. Average uplink throughput obtained via blended textile antennas at the user end for a bandwidth of 5MHz and 64 antennas at the base station in a realistic cellular scenario [2] (See also Sec. IV-D). The different applications that can be supported are highlighted based on [3].

Fig. 2. System model. Example of a blended antenna wearable where the antennas are deployed in the back of a jacket.

(a)

(b)

Fig. 3. Textile antenna planar array simulated performance: (a) S -parameter magnitude values for antenna placed approximately in the center of the planar array. The antenna matching is given S_{ii} and also the mutual coupling with the four antennas surrounding up, down, left, right (S_{ij}); (b) Deployed antenna set and example of radiation pattern.

Fig. 4. Average achievable rates in the uplink in an idealistic scenario: (a) Performance trade-off for different number of blended antennas deployed at the wearable $M = \{1, 10, 20, 40\}$. The BS antenna configuration is fixed to $N = 4$ representing a nowadays scenario; (b) Performance trade-off for $M = 40$ blended antennas deployed at the wearable. The BS allows different antenna configuration $N = \{1, 4, 8, 64\}$ representing the evolution of BS in future wireless systems.

Fig. 5. Percentile of users achieving a certain uplink throughput with a signaling bandwidth of 5MHz in a realistic cellular scenario [2] when the number of textile antennas range $M = \{1, 5, 10, 20, 40\}$: (a) Base station with an antenna deployment of $N = 64$; (b) Base station with an antenna deployment of $N = 4$.

Fig. 6. RF chains and processing board sketch.