3. Progress beyond the state-of-the-art

3.1. mmW antennas and front-ends

3.1.1 State-of-the-art

- **Integrated and beam steering antennas**

In-Package integrated antennas supporting Gb/s data rates have triggered a lot of interest over the last 5-7 years in the 57-66 GHz. The main design challenges are radiation gain and efficiency, reflection bandwidth of the radiating element and close integration with the RF front-end to minimize interconnect issues. Many antenna variants have been implemented on different substrates: glass [4], LTCC [5], [6], multi-layer laminates [4], [7], [8], [9], and semi-conductors (silicon, e.g. [10]; CMOS, e.g. [11]; GaAs, e.g. [12]).

Beam steering antenna arrays have been also demonstrated: (1) phased array antennas [5] , [13], [14],[15] , with a number of elements varying between 4 [13] to 48 [15], (2) Switched beam antennas on LTCC [8], [16], on LCP substrates [17].

Most of the switched-beam antennas are based on Butler matrices fabricated on CMOS (e.g. [18]) or organic substrates (e.g. [19], [20], [21]). Rogers RT/Duroid 5880 or 6002 substrate materials have been preferred for many years. A recent trend consists in using LCP, Isola Astra or RO 4003 substrates. CMOS-based beam formers, although highly integrated, suffer from prohibitive insertion loss.

Note: we do not provide here a state-of-the-art on highly-directive antenna systems since backhauling is not considered in M^5HESTIA.

- **mmW antennas for M-MIMO application**

No mature antenna solution, compliant with a large number of radiating elements or beams, has been proposed so far. Ref. [22] presents a beamforming architecture combining an analogue beamformer and a digital precoding with multiple RF chains using theoretical isotropic radiating elements. Furthermore, a multi-beam transmission diversity scheme is proposed for single stream transmission for single-user MIMO operation. Mutual information (MI) of several MIMO antenna selection configurations has been studied based on 60-GHz MIMO channel measurement data in [23]. Several array shapes with different numbers of radiating elements have been considered. The effect of the switching network (either lossless or with realistic losses) as well as the influence of the selection criterion [either maximum signal-to-noise ratio (SNR) or optimum capacity criterion (OCC)] has been analysed. It is found that, in the best case (optimum capacity criterion and lossless switching network), antenna selection can increase MI by up to 127% as compared to traditional MIMO systems. Nevertheless, under more reasonable conditions (maximum SNR criterion, realistic switching network) the MI decreases drastically, with a maximum improvement of only 11% as compared to traditional MIMO systems.

An interesting breadboard has been presented in [24], with a 24 slot antenna with 12 elements each for Tx and Rx parts and a two-bit phase shifter per element. By applying suitable phase weights to the 24 elements, independent transmit and receive beamforming has been demonstrated. In addition, a 60-GHz band 4-element array using phase-oversampling vector modulation has been implemented in 65-nm CMOS technology [25]. A digitally-controlled semi-lookup table method is proposed to compensate for non-ideal characteristics in circuits, antenna arrays, and interfaces. An accurate and high resolution control on gain and phase has demonstrated. The receiver features a noise figure of 5.6 dB and 3.5° phase resolution at a back-off of 3 dB. It dissipates 178mW from 1-V supply and obtains 18.5 dBi gain for each channel.

3.1.2 Progress beyond the state-of-the-art

Various innovative antenna systems will be developed and implemented:

- One Single Input Multiple Output (SIMO) system for channel sounding,
- One Multiple Input Single Output (MISO) system for M-MIMO in the 60-GHz band.

These antenna architectures will be based on analogue and/or digital beamforming techniques. To our best knowledge, there is no M-MIMO mmW platform deployed today. Only theoretical analyses present the interest of M-MIMO in the 60-GHz band. In a recent paper published in May 2015 by KTH Royal Institute [26], a SDR 60-GHz front-end has been proposed for MIMO (2 antennas) experimentation. The performance limits of this platform are clearly identified for further extension to M-MIMO application:

- Phase synchronisation of each 60-GHz front-end,
- Optimisation of the inter-element spacing (ideally half wavelength) for beamforming. This space constraint is really challenging for integration of all active circuits (amplifiers, VCO, mixers, etc.).

These two points perfectly match with the design constraints identified for the 60-GHz front-end for M-MIMO communications.

3.2. mmW outdoor radio channel modelling and characterisation

3.2.1 State-of-the-art

Today there are only a few publications on outdoor MIMO in the 60-GHz band, and even less concerning the so-called mmW M-MIMO. However, probably many teams around the world are now investigating mmW M-MIMO because the huge expectations. Channel sounding for indoor MIMO scenario has been widely investigated yet, e.g. [27].

The most important innovation concerns the use of mmW for outdoor scenarios. In a seminal paper published in 2013, Rappaport *et al*. advocates that mmW are good candidates for 5G, even for outdoor scenarios [28], [29]. At that time, this loud and not so obvious claim was relying on intensive measurement campaigns performed at New-York University at 28 GHz and 38 GHz. This team has also conducted more recently propagation measurements in E-band (60-90GHz) for both mobile and backhaul scenarios in the dense urban environment of New York City [30]. Measurements were made for both mobile and backhaul scenarios with separation distances up to 200 m. It was shown that the mmW spectrum, specifically the E-band, could also be used for future cellular communications by exploiting multipath in urban environments with the help of beam-steering and beam combining. This corresponds to great promises for capacity increase w.r.t current wireless network infrastructure.

In [31] the M-MIMO performance is studied from actual measured data at 2.6 GHz. The antenna array placed on the base station side is made of a circular array of 128 patch antennas. The receiver side is a virtual linear array with 128 omnidirectional antenna positions.

Having good channel models is always required for designing efficient communications systems; this is particularly true for outdoor mmW for which very few results are available. Knowing the channel over the following dimensions (power delay profile, power angular profile) and their evolution along different time scale is crucial for making sounded assumptions on the PHY layer design. Propagation loss at mmW leads to weak distant reflections and dominance of rays that are close to the direct path. This requires new approaches to characterize channel mobility and Doppler effects. The sparsity of the mmW radio channel makes the deterministic or quasi-deterministic approaches very attractive, or even compulsory. This is one of the conclusions on mmW channel modelling derived by the MiWEBA project [32]. MiWEBA has proposed and developed the methodology of Quasi-Deterministic (Q-D) channel modelling [33]. The approach consists in calculating several strongest propagation paths based on the geometry of the deployment, locations of Base Stations (BS) and User Equipment (UE) in a deterministic manner. The effect of random objects (far walls cars, lampost, etc.) is taken into account through so called random rays. Modelling analysis and measurement of mmW MIMO are presented in [34]. This work constitutes provides a good theoretical formalism for modelling the transmission channel including a realistic mmW MIMO antenna array. This approach deserves to be connected with radio propagation tools such as ray tracing based radio propagation tools. Indeed, ray tracing tools are becoming very important in the mmW context. In [35] it is demonstrated the utility of using ray tracing tool in mmW channel data interpretation and [36] in the same line of thought goes even until introducing the concept of ray tracing-aided beamforming.

3.2.2 Progress beyond the state-of-the-art

Rappaport *et al*. reported on outdoor mmW measurement campaigns in [28], but without considering M-MIMO perspectives. Ref. [31] described M-MIMO measurement results but at much lower frequencies. What makes M^{5}HESTIA extremely innovative is the threefold combination "**outdoor**" + "**mmW**" + "**multi-user M-MIMO**".

Moreover, regarding the channel modelling task, what is going to be highly innovative is that we will properly take into account the effect of RF front-end topology and impairments in the transmission channel. This modelling endeavour will be done by taking advantage of the wide and complementary expertise of the consortium and following closely the discussions and technical choices that will be decided in the 3GPP RAN. M^{5}HESTIA project is going to investigate also along research paths as such proposed in [36] and hopefully getting much further.

3.3. M-MIMO systems and signal processing

3.3.1 State-of-the-art

As far as signal processing is concerned, there have been a huge amount of studies since the pioneering work of Marzetta *et al*. [37] who demonstrated the promise to handle orders of magnitude more data traffics by using a very large number of active antenna elements. Many of them first sought the closed-form expressions of the performance of Massive MU-MIMO systems in the asymptotic regime, i.e. considering an infinite number of antennas (IQ links). Many convenient closed-form expressions for the achievable uplink or downlink spectral efficiency can be found, e.g. in [38][39][40]. In addition, many studies were dedicated to the search and the comparison of linear precoders (uplink) and combiners (downlink), trying to find optimal solutions trading off power gains against MU interference levels. In most of these first studies which can be found in the open literature between 2010 and 2013, the question of the number of supported users according to the number of active antennas was central, and the accepted ratio today for a fully SDMA strategy is about one order of magnitude [40]. Complementary to this aspect, numerous studies have been addressing the issue of channel estimation inaccuracies, namely considering the so-called pilot contamination effect between neighboring cells arising at high user density [41]. More recently, following the same general idea of pushing the limits of the number of users addressed in parallel, many authors posed the problem of resource allocation in Massive MU-MIMO systems and have proposed algorithms based on user clustering strategies mixing the SDMA capability of the M-MIMO systems with more traditional approaches such as TDMA or FDMA [42].

However, all these first contributions have assumed favorable propagation conditions by considering very simple channel models built from decorrelated complex Gaussian fading per spatial link. Therefore, more recent studies include more reasonable assumptions to point out the practical limitations of M-MIMO strategies in realistic environments [43]. Hence, performance evaluations based on measurement campaigns in the 2-5 GHz bands were conducted as well as analytic performance derivations based on more elaborated channel models. For instance, a widely-used channel model, commonly referred to as "one-ring model", and adapted to large scale antenna situations in [44] integrates a correlation matrix for the transmit antennas assuming a uniform distribution of scatterers surrounding each user individually. However, such kind of model considers non-line-of-sight transmission only, and neglects the inter-user channel correlation which is however of high importance when dealing with MU transmissions.

On one another hand, other studies have recently addressed the problem of complexity, which remains one of the main drawbacks of large-scale antenna systems. One interesting approach then, first proposed many years ago in the context of smart antenna design [45], is to combine analogue and digital precoding functions to reduce the number of required RF chains, and thus the number of mixers, amplifiers, converters, etc. Analogue beamforming is much less complex than pure digital beamforming, but has poorer performance, because it does not allow controlling the magnitude of the beamformer elements. Indeed, adjusting only the phases of the radio signals may not be able to control adequately the interference level between users, as the beam direction of one particular user might be severely jammed by the side beams of other users. Hence, a promising approach in a M-MIMO context, is to consider a joint optimisation, involving baseband precoding/beamforming techniques to jointly steer the beam patterns and suppress the interference for all users. Such an approach has very recently been studied for instance in [46][47].

3.3.2 Progress beyond the state-of-the-art

From the already-existing studies about M-MIMO systems, we can claim that very few of them deal with mmW transmissions. Most of the published works only point out new challenges (e.g. [48]) or are based on simple models as described above (e.g. [49]). Strong assumptions currently used for lower frequency bands, typically around 2 GHz, may not be valid in realistic mmW transmission scenarios, and might lead to inaccurate or even erroneous conclusions about system capacity and performance. Hence, many well-known results about M-MIMO system might have to be questioned.

In M^{5}HESTIA, a lot of effort will be put by considering a more adequate and refined channel model into the system model in order to design estimation strategies and precoding schemes that take advantage of the particular mmW channel structure. The latter is in fact expected to be sparse in the angular domain, leading to low-rank channel matrices [43][50]. It is then expected that taking this into consideration, as accurately as possible, will drive **the design of new signal processing algorithms, in terms of channel state information tracking as well as concerning multi-user spatial multiplexing.**

In a complementary way, due to the implementation costs and technical challenges at the RF front-end level in mmW, studying the hybrid beamforming concepts as addressed in [47] are of great interest. Based on the mmW propagation specificities, it is expected that multiple antenna systems will have to exploit preformed beams to face strong free-space power attenuations. However, many practical constraints have to be taken into account such as DAC resolution, power loss in the RF chains due to beamforming units, local oscillator phase noise, etc. Hence, **it will be studied to which extent hybrid analogue/digital M-MIMO system architectures could perform efficiently, and general conclusions in terms of global performance/complexity evaluation will be drawn.**

Last but not least, most of the studies about M-MIMO systems are based - by default - on a flat fading channel assumption, thereby implicitly assuming a combined use with a multicarrier waveform as OFDM for example. However, owing to the use of convenient beamformers, M-MIMO channels tend to become noise additive only. **The question of the waveform has thus to be raised, multicarrier ones being essentially powerful to deal with multipath channels**. These aspects have only been addressed in very few works (e.g. [51]) and have to be specifically studied in the case of mmW propagation. Indeed, it has to be noticed that single carrier modulation has already been proposed in the framework of IEEE802.11.ad standard for WLAN operating at 60GHz in indoor environment.

3.4. mm Waves M-MIMO HW platform

3.4.1 State-of-the-art

Table 2 provides a concise overview of current M-MIMO proofs-of-concept (PoC) developed so far. From this table, we can notice that most of the PoC have been implemented at much lower carrier frequencies, below 10 GHz.

Samsung has prototyped a 4×8 antenna array at 27.925 GHz that could be concatenated to increase the number of antenna elements beyond 64. Based to on measurement campaigns, this antenna array was used to establish a channel model at 30 GHz. Moreover, data rates throughput transmissions have been demonstrated until 1 Gb/s up to 2 km in Line of Sight (LOS) environment with mobility [55].

Huawei showed 2 M-MIMO 'Mock-Ups' at the Mobile World Congress 2015: squares of N×N (N antenna>8) mm antennas (at 60 GHz) and one panel of 128 antennas, 7-6cm flat intended for LTE TDD 3.5 GHz transmission. Ref. [3] proposes a massive MIMO 'Mock-Ups' but does not integrate any RF front-ends parts (only digital processing implementation).

Regarding mmW real-time implementations, we can mention that some products exist for Wi-Gig (IEEE 802.11 ad) systems [60] for indoor environments. However, the number of antennas is limited to 8 at Tx and Rx sides in the 60-GHz band allowing to achieve more than 4 Gb/s data rate across a 1.7-GHz bandwidth.

	ALU & RICE Univ. (ARGOS)	NI & Lund Univ.	NUTAQ	Samsung	Huawei & Univ. of Surrey (5GIC)	ZTE	Ericsson
Freq. (GHz)	2.4	1.2 to 6 (BW=20MHz)	up to 6	27.925	3.5 GHz TDD	2.555-2.655 (BW=20MHz) LTE-TDD	15
Antennas	64 / 96 (4x4 pattern)	Up to 128 (2x2 / 4x4 pattern)	up to 1000	Up to 64 (4x8 antenna array)	128 No RF yet 6-7 cm flat	128 64 ports (1port-2 antennas)	hundred of antennas
Size						90mm x 50mm x 120mm	
Performance claimed	Up to 32 users simultaneously		240 Gbps	1Gbps up to 2 km in LOS environment with mobility		64x8 MU-MIMO Total 300Mbps DL cell throughput 36-40 Mbps/UE	
Operator involved			DoCoMo	DoCoMo	China Mobile	China Mobile	Docomo
References	[52]	[53]	[54]	[55]	[56]	[57]	[58][59]

Table 2: Overview of current massive MIMO PoCs

3.4.2 Progress beyond the state-of-the-art

In the M^5HESTIA project, we propose to go beyond this state-of-the-art by addressing a full real-time HW demonstration of Multi-User M-MIMO at 60 GHz in outdoor environment, including adaptive antenna arrays (dynamic parameterization by digital precoding processing of the antenna RF chains) and advanced signal processing techniques implemented in base-band domain.

The HW platform will demonstrate how it is possible to focus the transmitted signal (and power) in a specific direction, limiting the interference between users. This demonstrator will allow to validate the propagation conditions in outdoor at 60 GHz (LOS or N-LOS) and then to determine whether 60 GHz frequency band can be adapted for outdoor fronthauling communications or more especially for high data rate backhauling as point to point communication (between base stations or access points for instance).

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