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Multi-antenna, Multi-node, Multi-RAT Architectures to Provide an Immersive Experience to the Early 5G Adopters

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***Abstract*—This paper discusses transceiver radio architectures for the 5G immersive experience and for three extended use cases that will be studied in the WP5 of the EU funded mmMAGIC project. The need to provide multi-antenna and multi-node solutions in the mm-wave spectrum is emphasized, as well as the need to encompass legacy and other complementary RATs in this 5G system. The hardware imperfections that should be tackled or worked around in these challenging radio systems are also highlighted.**

Keywords— 5G; Beamforming; Immersive experience; Multi- node; Multi-RAT; Hardware imperfections

I. INTRODUCTION

There is now a concerted push from research communities around the world to define 5G and to develop technologies to realize the 5G vision. Within the EU Horizon 2020 (H2020) research initiative, mmMAGIC is a flagship project looking at the adaptation of mm-wave spectrum (defined as 6-100GHz for the project) for 5G services [1]. Not only it will analyse the spectrum and develop channel models through numerous channel measurements, but will also design and develop radio technologies suited for these challenging radio conditions. The work package 5 (WP5) of the mmMAGIC project, where this paper originates from, is focussed on defining the transceiver architectures and developing multi antenna and multi node schemes to achieve the 5G performance in mm-wave bands.

It is generally accepted that 5G would encompass a far wider ecosystem than its predecessors, covering multiple vertical industries like transport, healthcare, retail and industry automation. However, the mobile component will still be of fundamental importance, particularly to the incumbent operators as this is their core business. 5G provides the operators an opportunity to enact a step change in user experience for the early 5G adopters. This will be quite revolutionary, as the ***initial*** deployments of previous generations did not quite mark a distinct break from the legacy systems or usher in new services.

The immersive multi-media experience promised by the emerging technologies can be a key 5G service that will differentiate 5G from the legacy systems. This immersive experience is expected to encompass UHD (Ultra High Definition) video, virtual reality and real time interactive gaming and other similar services [2-4]. The data rate, latency and other requirements (discussed later) are unlikely to be met by the (then) evolved 4G systems. So a 5G system supporting these requirements by design would mark a distinct shift in user experience for the early 5G adopters.

In a deployment sense, this immersive experience will first be provided in targeted coverage areas (or hotspots) where the demand for such immersive services will be higher. Thus the interworking between this 5G hotspot and the legacy systems to provide continuity of coverage and connectivity will be an important feature. Also to ease the capacity demand, the interworking (for off-loading) with other technologies like WiFi/ WiGig and D2D will also be important. This brings in the need for the 5G system design to support multiple Radio Access Technologies (RATs) and work around the constraints laid by this. We will also study 3 extensions to this immersive experience use case in terms of mobility, coverage and connection density.

In this paper we will look at the multi-antenna and multi-node transceiver architectures (in the work domain of mmMAGIC WP5) to support the above mentioned 5G immersive experience use case and the 3 use case extensions. As noted above, the considerations for multi-RAT architectures will come from the need to support other technologies for continuity of coverage and connectivity and provision of additional capacity. In section II, we will present the technical details of the immersive 5G experience use case and the 3 use case extensions. Section III will discuss the requirements placed on the radio (transceiver) architecture by the stringent KPIs of the use cases. Section IV will present multi-antenna enabling technologies that would be developed to support these requirements. In section V, we will discuss the related multi-node technologies. The hardware impairments in providing these enablers and possible solutions to these will be discussed in section VI. Finally section VII will provide the conclusions and further planned work.

II. THE IMMERSIVE 5G EXPERIENCE USE CASE AND EXTENSIONS

As noted above, the immersive 5G experience use case aims to provide a distinct improvement in QoE for the early 5G adopters. This will be considered as the baseline use case for the technical work in the WP5 of the mmMAGIC project. The deployment will be based on targeted hotspots, complemented by legacy systems for coverage and connection continuity. This HetNet (Heterogeneous Network) architecture provides unique benefits as well as limitations, which will be addressed during the course of work in this work package.

A. The key KPIs for the baseline use case

In determining the KPIs for this use case, we have to consider the likely requirements of the evolving immersive applications and the likely capabilities the evolving 4G systems would provide. Currently the 4k UHD video streaming services promoted in UK needs up to 40Mbps consistent data-rates (depending on video coding) [5], which is today only possible with wired/satellite connections. With 8k-UHD and further evolutions, these requirements are likely to increase many fold. The IMT-Advanced specifications can provide around 10 Mbps user experienced data rates and 1Gbps peak data rates for static users. The latencies supported by IMT-Advanced are around 50ms. The proposed key KPIs for this 5G use case are: 100Mbps as a baseline data rate, while the peak data rates (on demand) can be up to 20Gbps and the latencies to be below 10ms. The large variance in data rates is to support the potential requirements of the evolving immersive 5G applications and also to account for the possible variations in radio link quality. The 20Gbps peak rate can seem excessive at first glance. However, other technologies like WiGig are already proposing peak rates of around 7Gbps and IEEE 802.11 NG60 study group [6] are considering data rates above 20Gbps for short range applications. New services will develop in this context and 5G needs to stay competitive with such data rates.

These early 5G small cells with targeted coverage, deployed on mm-wave spectrum, would probably have a second layer of coverage provided by 3G, 4G or even sub-6GHz 5G systems. Thus, the 5G small cells will be supported by macro/micro cells from these technologies. The interworking, handover coordination between these 5G small cells and the underlying network will be an important feature for this use case.

The KPIs are summarized in Table I below.

Table 1: Quantification of the main KPIs for the baseline use case

KPI	Requirement	Comment
User data rate in DL	>100Mbps	The user could demand higher data rates up to 20 Gbps.
User data rate in UL	>50Mbps	The user could demand higher data rates up to 10Gbps.
Connection density	~10000/km^2	Estimated 1000 active users in an area of 0.1 km^2. Supported by 40 users in each of 25 small cells.
Traffic Density	1.7/0.85Tbps per 0.1km^2 coverage area (17/8.5 Tbps per km^2)	For downlink and uplink, respectively. It is assumed that 50% active users demand around 100 Mbps in DL, while 4% users demand around 10-20Gbps. Please refer to [7] for more details.
Mobility	0-5km/h	The mobility is low, most users moving at pedestrian speed.
Availability	Above 95%	Enabler for 5G services, as a step change from 4G.
Reliability	Above 95%	Enabler for 5G services, as a step change from 4G.
Latency	Below 10ms	To support 5G real time gaming and VR applications.

B. Gap from the current technology

The user experienced data rates should improve by a factor of 10 and the peak data rates should improve by a factor of 20 from the current LTE operational levels. The latencies should be reduced by at least a factor of 5 to achieve (near) real time experience for immersive 5G services. One of the deployment challenges (w.r.t. LTE) would be the densification of the small cells. Even with the LTE-A Release 13 predicted levels [8], around 25 small cells per coverage area (typically 0.1km^2) would be required to provide the necessary capacity and the number of connections. The mm-wave technologies do bring in other benefits, like higher spatial re-use. Interference control and backhaul provision technologies will also have to significantly improve from the current state-of-the-art.

In this comparison, the small cell specific LTE state of the art technology has to be referenced. LTE-Hi (LTE for Hotspot and indoor) is an emerging technology [9], with the specifications expected to be finalized in LTE release 13. A recent paper by experts of two leading operators [8] estimated that this technology will achieve 838Mbps peak data rates with 100MHz compound (carrier aggregated) bandwidth. The cell sizes they foresee are up to 50m radius. The link spectral efficiency is already very high (8.38bits/Hz). We can expect the combined value of density and spectral efficiency (area spectral efficiency) to go up by a factor of 4 under favourable conditions in early 5G. This factor of 4 is considering that the multi-antenna phased arrays having to mostly support SNR gain in beamforming, but also achieving higher spatial re-use/multiplexing gains. So only to achieve the 20Gbps peak data rate, the bandwidth needs to go up at least by a factor of 6. Thus, the initial bandwidth requirement only for this peak data rate provision (for a single user) would be 600MHz. Some insights into the average bandwidth requirement is provided in [7], through a detailed calculation of the possible user data rate distributions and looking at the joint cumulative distribution functions. According to this analysis, the average bandwidth requirement to satisfy 95% of the active users is 860MHz and for 99% of active users it is 1.15GHz. This gap analysis reveals a significant need for performance improvement and also the need for much wider bandwidths than what can be foreseen for evolved LTE systems. Thus this is an opportunity and a design challenge for 5G research to come up with an architecture and enabling technologies to meet these requirements.

C. Use case extensions

The baseline use case captures targeted coverage areas, typically 0.1km^2 in area. These initial 5G deployments are considered to be supported by an underlay of larger cells from legacy networks. This would imply multi-RAT, multiple air interface systems coordinating with the 5G small cells. When we move towards extended coverage, possibly this legacy support will diminish, reducing these constraints. But they will open up new challenges for the multi-antenna/node architectures we will be studying in WP5. The coverage extensions will be studied up to the premise of providing 5G everywhere as envisioned in the 50+Mbps everywhere use case. The premise of ‘everywhere coverage’ extend to dense urban and sub-urban environments, with connection densities of 400-2500 per km^2. 50Mbps is an indicative data rate which could peak even at 1Gbps. The mobility may also increase to typically 50km/h, a practical limit for urban vehicles.

The mobility levels in the base-line use case are pedestrian at 0-5km/h range. As the coverage is expanded, it is only logical to study higher mobility options. Providing mobility options with legacy network support opens up new challenges with respect to provision of demanding KPIs. For moving 5G cells, the backhaul provision with legacy network support will be an area we will study in this WP. Again, as with coverage, we would incrementally study the increasing ranges of mobility from 30km/h up to 500km/h in this work package. The DL/UL data rates considered would be 100/50Mbps respectively. The connection densities would be around 2000 per km^2.

As 5G evolves, it will be required to support very high connection densities. These can be regular/irregular events like football matches and musical concerts for example. This level of connection densities may need the other KPIs to be less stringent to achieve the overall system performance. In WP5, we will look at the particular challenges placed on multi antenna/node architectures by these very high connection densities. At the extreme, we will be looking at 15 times higher connection densities from the baseline use case, i.e. 150000 per km^2. The average connection density for this use case is at 30000 per km^2. The traffic pattern is UL heavy (assuming lots of video/content uploads from events) with 50Mbps in UL and 25Mbps in DL. The mobility remains the same as for the baseline use case, pedestrian. The use of off-loading technologies like WiFi, WiGig and D2D are expected to play a significant role in easing this capacity and connection density demand of this extended use case.

Further details of all these use cases can be found in the first mmMAGIC public deliverable [10].

III. REQUIREMENTS ON THE RADIO ARCHITECTURE

The KPIs defined in the previous section for the 5G immersive experience use case determine the requirements on the radio architecture and call for disruptive changes, with respect to current 4G systems, enabling the most efficient exploitation of mm-wave spectrum resources and opportunities for highly-flexible large-scale multi-antenna systems.

The baseline use-case assumes mm-wave small cells with a coverage radius of 100-200m (0.1km^2) in outdoor conditions but should be able to address indoor deployment as well with more complex propagation channels (larger number of path components and more significant blockage issues). Most probably, its implementation will involve multiple radio architectures accounting for the diversity of equipment at user level (mobile user equipment, UE) or infrastructure level (access points (AP), backhaul radios).

Generally, due to battery life restrictions, the bulk of the complexity needs to be placed at the AP side, whereas the UE needs to be kept simple and transparent to the multi-antenna environment of the AP. Critical requirements for transceivers embedded in future mobile terminals such as smartphones, tablets or other portable user equipment are very low power consumption (less than 1W), miniature size (few cm^2 maximum) and low cost. Such constraints, especially the cost and power consumption factors, preclude the usage of multiple antenna systems with a large number of elements, such as those that have been developed over the last decade for high-definition video or indoor communications in the 60GHz band, even though their size would fit in most terminals. In contrast, small-cell AP would benefit from more relaxed specifications on these factors but, as a counterpart, much higher mm-wave performance specifications (transmit power, radiation gain, beamforming functions). These higher specs will help achieve the link budget and other requirements in terms of data rate, communication range, coverage and multi-user handling. So we will be investigating mm-wave radio architectures where the complexity is more asymmetrically focused on the base station (or AP) side.

A lot of research has been performed over the last decade in the domain of mm-wave CMOS radios and in-package integrated antennas, driven by the progresses of low-cost silicon integrated circuit and packaging technologies and the perspective of mass-market consumer or telecom applications.
For UE, single-path transceiver radios associated to a fixed-beam antenna or a small antenna arrays with switched beam capability are targeted in a single and compact package. The antenna shall exhibit wide angular coverage to guarantee the robustness of the mm-wave link as a function of the terminal orientation with respect to the AP direction and the user's hand position. This issue can be further addressed by including several modules in the terminal (e.g. front and back side of the terminal), and dynamically selecting the most favorable module.

At base station level, more complex transceiver systems will be required as compared to user equipment, certainly with a large number of antennas and hybrid beamforming capability, i.e. combining analog and digital beamforming. In this case, multi-module architectures will be favored in order to avoid the cost and reliability issues of large-size RFIC chips and packaged modules, and to provide a good scalability of the technical solution as a function of the small-cell specifications (range coverage). Antenna gain values, i.e. number of antenna elements, in these cases will be derived from link budget analysis based on the selected frequency band, the expected antenna gain at user equipment level, the expected communication range (small-cell radius), the signal-to-noise ratio, propagation conditions and outage statistics. Requirements on other components of the radio transceivers are to be derived as well, in particular for power and low-noise amplifiers, oscillators and frequency synthesis, data converters.
The extended use cases described in Section II will be achieved through several means. First, a higher AP density will be required to provide a better coverage approaching the 'everywhere coverage' objective, a higher user density up to the extreme case of massive crowds gathered in public events such as in sport competitions, a better redundancy to mitigate blockage effects and a smoother handling of mobility. Second, a reconfigurable backhaul mesh network will be required for optimal management of the network capacity and this will impact the backhaul radio architecture as fixed wireless links will be replaced by adaptive steerable links, possibly with multiple simultaneous beams. Finally, the network architecture will be required to handle moving APs installed on board trains, cars, buses, etc. for high speed mobility use cases and this will have an impact on the beam steering capabilities and algorithms of backhaul nodes with very challenging latency issues.

Mobile users expect a multi-RAT operation combining the new 5G standard in mm-wave band and legacy 4G LTE-A standard in the sub-6GHz bands as well as other RATs such as WiFi and D2D. Current UE are using multi-RAT transceiver chipsets with multi-band antennas, which are feasible because these standards are implemented in similar frequency bands and similar architectures but it is likely that mm-wave 5G transceiver and antenna systems will have to be independent chipsets due to their very different architecture (large number of antennas) and requirements for a close integration of the transceiver and antenna elements for efficiency. The hardware impairments and limitations in these chipsets individually and when they are combined together will also form an important part of our investigations.

IV. MULTI ANTENNA ENABLING TECHNOLOGIES

It is well known that mm-wave propagation faces more severe challenges than systems operating at lower frequencies. On the one hand the free space path loss based on Friis' law increases with the square of the frequency due to the antenna aperture size reducing at the same rate. Also it is known that the penetration losses through buildings and other clutter increases with higher frequencies. However, since the size of the antenna elements decreases with the frequency, the number of antenna elements that can be packed into a given area can also increase with the square of the frequency. Compared to lower frequency systems and given a physical antenna aperture, this implies that communication at higher frequencies using larger antenna arrays has the potential to more than compensate the adverse effects noted above. In fact, to overcome the propagation effects at higher frequencies including shadowing and higher penetration loss, antenna arrays are expected to be deployed at both the transmitter and receiver [11]. Due to cost, complexity and practicality issues noted in section III, the array sizes will possibly be larger at the base station (or AP) side than at the handsets. This aspect highlights the importance of multi-antenna techniques for enabling the air interface of future communication systems. This implies, nonetheless, the need of directional transmissions which imposes non-trivial modifications to the system design compared to current networks operating at lower frequencies. The challenges will be particularly high in the dense urban/ crowded hotspot like environments we are considering for the base line and other use cases.

Due to the large dimensionality of the transmit/receive antenna arrays and the large bandwidths envisioned for mm-wave communication, there is a need of a large amount of RF chains including high resolution converters (DACs/ADCs) with a high sampling rate possibly in the range of Giga-samples per second (Gs/s). Nevertheless, converters with a high sampling rate and with high resolution are costly and power hungry. The use of such devices comes actually at odds with the goal of higher energy efficiency in future wireless communications, the so-called Green communication. To deal with this bottleneck, the resolution of the converters could be decreased and hence, the transceiver and the air interface should be designed such that the coarse quantization of the converters is taken into account, for instance with low resolution ADCs at the receiver [12]. Another possible approach to address this bottleneck consists in reducing the number of RF chains, i.e. less converters, by employing hybrid beamforming [10], where part of the beamforming operations are performed in the analog domain and the other part in the digital baseband as shown in Fig. 1. The processing in the analog domain can be performed via a network of phase shifters or switches. Moreover, the analog processing could also be performed in baseband with multiplications performed with Gilbert cells. Although fully digital beamforming delivers the maximum performance, this comes at the expense of implementation complexity, power consumption and cost since one RF chain is required per transmit/receive antenna. On the other hand, the transceiver design based on the hybrid beamforming architecture is able to provide a trade-off between performance and implementation complexity as well as power consumption.

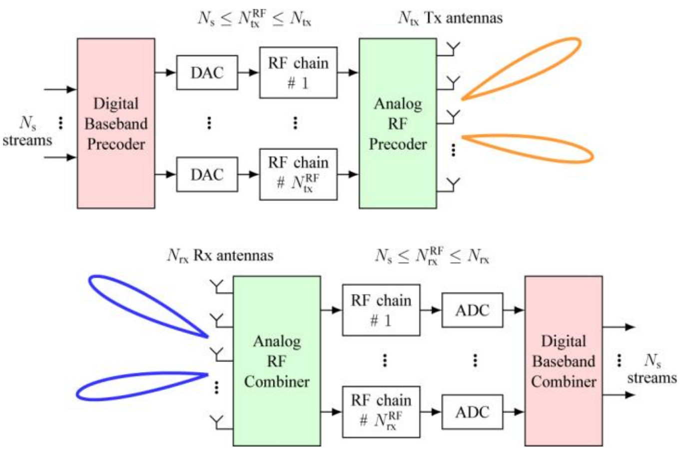

Figure 1: Hybrid beamforming where the beamforming is split between the analog and digital domains.

Another consequence of the large number of antennas required in mm-wave systems is the increased difficulty in acquiring channel state information. On the one hand we have that aiming to estimate all the entries of the channel matrix as conventionally done for smaller scale MIMO systems would eventually lead to large training overheads due to the large number of antennas. However, the channel at higher frequencies is expected to be sparse since the signal arrives at the receiver through a small number of scattering clusters [13]. This implies that the large channel matrices at mm-wave frequencies can be in fact expressed with a reduced set of parameters such as the angles of departures, angles of arrivals and path gains of each of the few paths. To reduce the training overhead, the sparsity nature of the mm-wave channels needs to be taken into account to devise novel channel estimation algorithms, for instance based on compressed sensing techniques [13] or schemes which take the inherent spatial structure into account.

Another important aspect to consider for channel estimation in mm-wave systems is that depending on the employed transceiver architecture, it might be very difficult to estimate the actual mm-wave channel. For example, when considering hybrid beamforming the channel seen in the baseband can only be viewed through the constrained analog beamforming at both sides of the link. This limitation not only leads to the need of designing appropriate training and estimation schemes for obtaining information about the channel, but in addition the transceiver algorithms should take this aspect into account [11].

For setting up the directional transmissions, the sparsity of the channel can also be exploited by performing beam-training, where the transmitter and receiver iteratively try to find the best pair of beams for the transmission and reception. Such schemes which have initially been devised for single link transmissions are to some extent semi-blind with respect to the full channel knowledge. For instance, in beam-training protocols based on a hierarchical search such as the ones proposed in IEEE 802.15.3c and IEEE 802.11ad, the transmitter and receiver might be unaware of the existence of a second strong path. Such additional information might be essential for more advanced transceiver algorithms.

Pertaining to the previous discussion, such further knowledge about the channel can aid in guaranteeing the link quality, since in case of a sudden blockage of the main path, the transmitter and receiver would not need to perform again the search for the best optimum beam pair. Techniques for acquiring or tracking channel information from several paths becomes of interest in such situations [14]. To this end, one could contemplate a multi-beam transmission where the user is able to receive information from different BS as well or the transmission takes place just on a single path, with the additional tracked paths/beams serving as backup links in case of a sudden blockage of the main path [15]. This type of techniques can be very useful particularly in the higher connection density use case, where (like in football matches) the users are seated most of the time, but the occasional standing up/ movements can block the main path for the radio links.

Since mm-wave communication requires directional transmissions to overcome the propagation effects at higher frequencies, user tracking becomes a challenge due to the use of narrow beams. Some schemes have been proposed to enable high mobility with narrow beams including techniques based on prediction [16]. In certain scenarios, however, many of the mobile users are actually travelling in the same vehicle, for instance in a high speed train. To this end, a mobile hot spot scenario can be considered to address the service of the users in the vehicle. Instead of trying to track all the users in a train, the BS basically sets up a (backhaul) link to an access point on the train, from where the transmission to the users is distributed inside the train. In this case, the known trajectory of the train can be employed for facilitating the beam tracking to the access point on the train [17]. A similar extension can be envisioned for a bus, whose route can also be known before hand or is limited to certain directions. This is of particular interest to the moving hotspots use case.

Despite the generic and use case specific challenges mentioned before, the potential of mm-wave communication can be unleashed if a careful and appropriate system design is performed, including the multi-antenna transceiver design.

V. MULTI NODE ENABLING TECHNOLOGIES

Previously, we have seen how the highly directional transmission leads to some challenges for the implementation of mm-wave systems. On the other hand, due precisely to the highly directional transmissions, it is often argued that the interference for mm-wave cellular systems might not be so detrimental as compared to current deployments at lower frequencies. However, whether interference plays a significant role or not, actually depends on the deployment, i.e. on the BS density as well as the capabilities of the antenna array at the users. In fact, due to the limited range of mm-wave communication, a high BS density might be required to achieve an acceptable coverage. For ultra-dense deployments, users might have a line-of-sight to several BSs, eventually leading to higher interference, in particular if we need to accept a less precise hardware-constrained (e.g. due to phase noise or limited DAC/ADC resolution) beamforming approach. Indeed as pointed out in [18], increasing the BS density after a certain point does not lead to an increase of the SINR. In this case, interference management via multi-node coordination becomes relevant.

Nevertheless, in contrast to the traditional multi-node cooperation at lower frequencies, due to the sparse multipath and high penetration loss the main goal of multi-node coordination at mm-waves might be to reduce signal outage due to sudden blockages and avoiding intermittent interference, instead of simply providing higher data rates. With peak-power limited mm-wave nodes, there will also be coverage gains due to increased aggregated power using multi-node joint transmission.

Key challenges and opportunities for multi-node cooperation among mm-wave nodes are to optimally and adaptively cluster the network and user nodes into cooperation areas for spectral efficiency, energy efficiency and load balancing, e.g. using the approach in [19]. To support such dynamic clustering, tight interaction and co-design with the backhaul network and network architecture is crucial. In particular, with mm-wave, less reliable, non-line-of-sight backhauling and fronthauling, there is a potential, and need, to co-design the access and the backhaul/fronthaul network to optimally and adaptively support a suitable centralized/de-centralized/distributed cooperation strategy for the particular usage scenario. Multi-node cooperation can also help to support higher mobility with seamless user experience at mm-waves, using a soft multi-node handover strategy, provided efficient solutions are identified for multi-node beam tracking and cluster reformation techniques.

Still, a consequence of the limited range of mm-wave communications is the fact that a stand-alone system might not be able to provide acceptable coverage, despite joint transmission and reception among the mm-wave nodes, in a wide area and across several scenarios. However, these systems will also be investigated in the mmMAGIC project to fully understand such limitations and look for potential solutions. To this end, mm-wave networks might need to be mostly heterogeneous in different facets such as in spectrum and deployment including distinct transmit power, processing capabilities and support for different radio access technologies (RATs) [20].

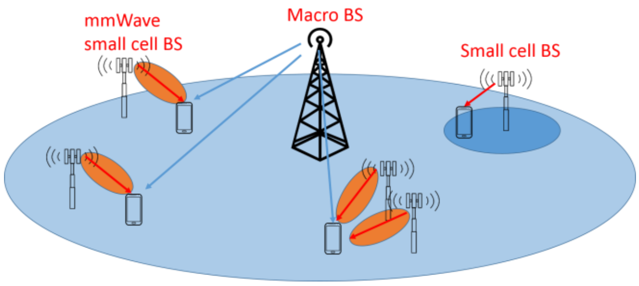

Figure 2: Illustration of some multi-node cooperation options

In such HetNets, multi-node cooperation among the multi-layer network nodes would be beneficial, as illustrated in Fig. 2 above. In particular, one could consider employing legacy systems at lower frequencies for control channels, which do not require high capacity link but rather need to guarantee a high degree of availability and reliability. Additionally, legacy systems can also be employed for the transmission of broadcast signals and for synchronization, due to the larger coverage they can provide. The multi-node coordination in mm-wave HetNets is nevertheless not a trivial task since for its feasibility a higher degree of complexity is necessary as well as possible higher power consumption.

VI. HARDWARE IMPAIRMENTS AND POSSIBLE SOLUTIONS

In the design of mm-Wave based wireless access networks for immersive applications – cost and energy consumption aspects may necessitate a design where hardware impairments are allowed to impact performance (e.g. the FER at certain SNR).

The concept of "dirty RF" was popularized by the paper [21]. Dirty RF is the concept of compensating for non-ideal analog radio hardware in digital base-band processing. In some sense this idea was already employed in the form of digital pre-distortion of power amplifiers and compensation of effects such as I-Q imbalance. However, 4G mobile systems are largely engineered so that such hardware impairments only have a negligible impact on the performance. Allowing hardware impairments to degrade the performance (e.g. the FER at certain SNR) is actually a different concept from "dirty RF" where the emphasis is on digital compensation. The reason for allowing such degradation is of course to develop a system which is more cost and energy effective –and thus overall more attractive.

Digital compensation schemes add complexity and must be weighed against the improvement they provide. When applying massive number of antennas and high bandwidths per antenna, digital compensation schemes may in fact be less feasible in 5G systems than in 4G, due to the massive base-band bandwidths (number of antennas times bandwidth).

The need for a large number of antennas is evident from the increased path-loss based on Friis' law at higher carrier frequencies (for the reasons discussed in section IV). In addition to this, we may anticipate that the efficiency and power per antenna element is reduced. This is illustrated by Fig. 3 which shows a review of a large number of papers with power amplifiers designs in the mm-wave range (primarily in CMOS) from 2011 to 2015. A similar study with designs before 2012 was published in [22].

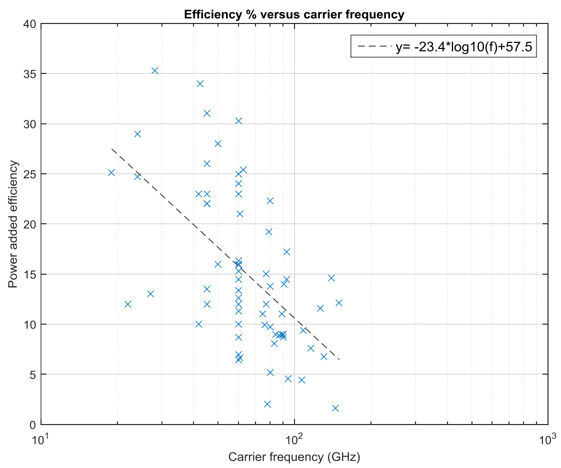

Figure 3; The power added efficiency obtained from 67 research papers written between 2011-2015. No switched designs were included. Each publication is represented by an "x". The dotted line is a minimum square error fit.

As the figure shows the efficiency is generally decreasing with increasing carrier frequency. Further investigation also shows that the power level per amplifier is generally decreasing as well. The power level can of course be increased by combining the outputs of several amplifiers – but only at the cost of power combining – which may further decrease efficiency, [22]. With a decrease in power and efficiency with increasing carrier frequency – the number of antennas must further increase to provide sufficient link budget. This may be seen as trading amplifier efficiency for a higher spatial efficiency.

In order to keep power amplifier efficiencies as high as possible together with limited possibilities for pre-distortion, operation in highly non-linear mode may be required. Countermeasures for such impairments include the use of waveforms with low peak to average waveforms. Massive arrays may also be used to reject interference between component carriers. Low-complexity pre-distortion techniques without oversampling e.g. through "data pre-distortion" may also be useful topic of research [23].

Phase-noise is an impairment that occurs due to noise in the components of frequency synthesizers: reference clocks (crystals), phase-frequency detectors, charge pumps, loop filters and voltage controlled oscillators. A widely used figure of merit for a voltage controlled oscillator as [24],

$$\mathrm{FOM_{OSC}} = \mathrm{S}(\Delta \mathrm{f})\left(\frac{P}{1mW}\right)\left(\frac{\Delta f}{f_c}\right)^2 \qquad (1)$$

where $\mathrm{S}(*)$ is the phase-noise spectral density, P is the power consumption of the device, f_c is the carrier frequency, and Δf is an offset frequency typically selected to 1MHz. The Figure of Merit (FOM) is a benchmark of how well the oscillator is designed.

The paper [25] showed that this FoM is relevant from a circuit analysis point of view and not only an arbitrary benchmark. The paper [25] further showed that the minimum FOM is given by, FOM=-173.1-20.log10(Q0) dB, where Q0 is the unloaded quality factor of the resonator. Equation implies a quadratic growth of phase noise with frequency. We would expect also an increasing $\mathrm{FOM_{OSC}}$ with carrier frequency, due to the difficulties, such as losses and parasitics, in making mm-wave integrated circuits. However, very efficient designs have been presented lately, such as [26] thereby possibly making this additional effect negligible. However, the quadratic growth is still important to consider. The phase-noise limits the minimum usable subcarrier spacing in multi-carrier and pre-coded multi-carrier modulation schemes – where a larger subcarrier spacing limits the maximum tolerable delay-spread. This also affects the maximum allowed ripple in the channel filters of the equipment. There are also MIMO aspects of phase-noise. Millimeter wave based 5G systems will employ massive number of antennas. Various hardware architectures may be considered supporting such systems. Each antenna may have its own mixer or groups (or all) antennas (sub-arrays) are served by a small set of RF-chains as indicated in Fig. 4 below. In the latter case all signals from the group of antenna elements will obviously be up/down-converted by the same local oscillator – while different groups may or may not use the same local oscillator. The alternative to the use of a single local oscillator is to distribute the reference clock and let each sub-array use its own PLL and VCO. With one RF chain per antenna element – each antenna may have its own local oscillator. These alternatives create different correlation properties in the phase-noise between branches.

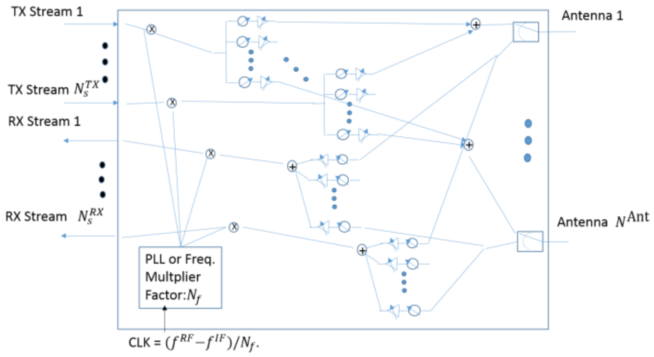

Figure 4: Illustration of sub-array architecture

In the simplest phase-noise model for OFDM systems, all subcarriers are rotated by a single phasor. In a MxN MIMO system with different PLLs and VCOs for each transmitter and receiver branch, NxM different common phase error rotations affect the MIMO channel. It may be necessary for the receiver to estimate all these phase noises to achieve optimum performance. This may be even more critical in multi-user MIMO systems when users are received at different power levels. In the paper, [27], the common phase noise components of two transmitter branches are tracked independently. However, it may not be necessary to track all the phase noises. An approach could be to instead rely on averaging of the phase-noise [28]. From a hardware point of view, distribution of the reference oscillator implies a simple distribution network but requires a duplication of the PLL and VCO functionality in the local oscillator – although the advantage of this duplication is the possibility to apply different carrier frequencies to different sets of antennas. Distribution of local oscillator signal avoids this duplication but requires a cumbersome high frequency signal routing which will require high quality (and therefore expensive) substrate materials in circuit boards. A third alternative is to distribute a "scaled local oscillator". For instance a 8 GHz signal which converted to a multiple of 8 GHz using a frequency multiplier, see e.g. [29]. However, our literature review suggests that frequency multipliers based on non-linearities are power consuming circuits – either through power consumption in the device itself or through the requirement of high input levels and high insertion losses. An alternative with lower power consumption may be injection locked frequency multipliers, see e.g. [30]. The impact of different LO distribution alternatives is indicated by Fig. 5 below which shows the SNR (from the viewpoint of the detector i.e. the SNR is based on EVM) in a 2x2 open-loop MIMO system when the same and LO is used in both receiver branches and when separate LOs are used. The phase-noise was measured end-to-end between using a Hittite HMC6000LP711E transmitter and HMC6001LP711E receiver circuit at 60GHz, while the channel is a simulated Rician channel with K-factor 10dB and both streams have an average SNR of 30dB. It should be noted that the scenario is chosen to emulate a scenario where each transmitter and receiver port is connected to an analog beamformer. The results show clearly the performance penalty of using different LOs in the receiver branches.

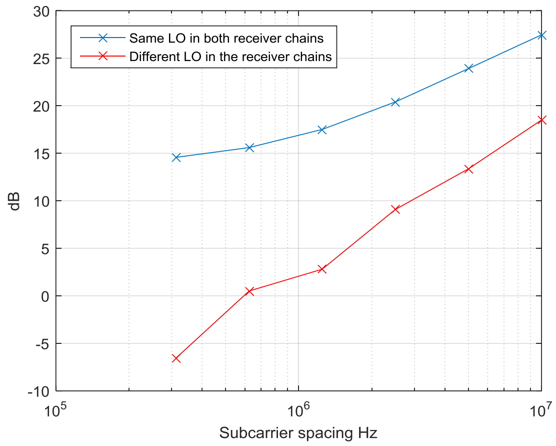

Figure 5: SNR from the viewpoint of the detector (-20*log10(EVM)), when taking into account subcarrier-to-subcarrier interference. The scenario is a 2x2 channel with 30dB average SNR on both stream operating over a 1GHz bandwidth.

VII. CONCLUSIONS AND FURTHER WORK

In this paper the architectures needed to provide an immersive experience to the early 5G adopters have been analyzed and the main challenges (and related solutions) have been pictured. The technical KPIs, fundamental to provide an immersive 5G experience (a use case studied by the mmMAGIC project), have been described and the extensions in terms of coverage, mobility and connection density have been proposed.

The radio architecture options for multi-antenna systems, required in order to fulfill the fundamental KPIs have been presented, and the challenges foreseen have been underlined. A fundamental enabling technology needed is represented by multi-antenna beamforming. Possible analog, digital and hybrid beamforming solutions have been described. The related challenges in terms of signaling overhead, user tracking and beam alignment have been analyzed. The multi-node enabling technologies to achieve the improved coverage and capacity required by the immersive 5G experience and the co-ordination problem have been described. Distributed multi-node MIMO in fact can provide more robust transmissions but requires an increased signaling overhead and advanced cooperation schemes. Finally, hardware impairments and limitations regarding the transceiver design have been discussed and possible solutions have been described.

Further planned work in this work package includes the development of multi-antenna and multi-node schemes to meet the KPIs and the architectural framework laid out here. There will also be work to model the hardware impairments and develop possible solutions to these impairments.

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