Challenges and Opportunities of mm-Wave Communication in 5G Networks

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***Abstract*—This paper provides an overview of research challenges and opportunities on mm-wave communication in the fifth generation (5G) mobile broadband networks. More specifically, different challenges, i.e. spectrum, propagation channel, cost and energy efficient aspects, from the perspective of mm-wave communication are discussed. Furthermore, insights on research opportunities of mm-wave communication in heterogeneous networks and multi-antenna transceiver technologies are provided. Based on provided overview, it can be concluded that mm-wave communication is a promising framework for further development and research towards next generation mobile broadband communication systems.**

I. Introduction

With ever growing volume of smart mobile devices, the increase of mobile data traffic is envisioned to explode 1000-fold increase by 2020 [1]. To fulfill the predicted traffic demand, the capacity of existing mobile broadband networks will be overloaded due to limited available spectrum in microwave band. Furthermore, to enable envisioned diverse and immerse mobile services, e.g. UHD/3D video streaming, cloud based services, augmented reality, for next generation networks and devices, new challenging requirements, e.g., in terms of throughputs, latencies and reliability, will be imposed for a entire system design.

To provide ubiquitous ultra-high data rate, i.e. multi-gigabit per second, mobile services, novel and revolutionary technology components and architectures need to developed. However, as technology improves, current spectrum for mobile services becomes fragmented. This causes problems in the mobile device design, e.g as large number of band combinations, space limits the number of antennas, especially as the frequency getting lower. Furthermore, existing spectrum for new mobile services becomes overcrowded. On contrary, mm-wave spectrum, i.e. 30-300 GHz, opens up an attractive opportunity to harvest large continuous chunks of spectrum with emerging mm-wave technologies for ultra-high data rate wireless communication. Up to today, mm-wave spectrum has not been effectively leveraged for the use of mobile broadband systems.

Despite the merit of large contiguous spectrum in mm-wave range, cellular type of communication with mm-wave technology has been considered as challenging. Mainly, this is due to unfavorable channel characteristics of mm-wave spectrum, i.e. large path loss, as well as impact of atmospheric absorption CO_2, O_2, and rain/fog/snow attenuation which are expected to reduce a service coverage significantly compared to existing broadband mobile systems. Additionally, mobility support has been limited. Traditionally, due to aforementioned reasons, potential deployment scenarios of mm-wave technology have been thought to be limited to a short range point-to-point communication in a line-of-sight (LOS) conditions with low mobility. However, recent results demonstrate that the mm-wave communication at 28 GHz band has been proven to be viable technology for a outdoor cellular communication [1][2][3][4][5][6].

Instead of optimizing a link efficiency as in existing 4G systems, the design focus of 5G networks has been shifted to towards overall network efficiency. In [7], multi-antenna transceivers and heterogeneous networks (HetNet)s have been identified as one of the key components to enhance network efficiency.

During recent years, multi-antenna transceivers have been extensively examined in many different wireless standards such as 3GPP LTE/LTE-A [8][9] as well IEEE 802.11e Wimax. Naturally, multi-antenna transceivers have been also actively examined in academia [10]. Due to the NLOS dominant propagation characteristics of channel below 5GHz, the work of 3GPP and IEEE 802.11e, has been mainly focused on techniques at transmitter and receiver sides that provide spatial multiplexing, diversity, interference mitigation gains. However, so far, research work in different standards at mm-wave 60GHz bands, e.g., IEEE 802.11ad [11], Wireles Gigabit Allilance (WiGig), have given a special focus on beamforming techniques cope unfavorable propagation characteristics.

HetNets provide an a paradigm shift to enhance network efficiency. The concept of HetNets has been actively researched during past years in industry and academia. HetNet concept has been part of different study/work items in 3GPP LTE-A, such as, Coordinated Multipoint Processing (CoMP) and small cells Rel-12 framework [12].

The major contribution of this paper is to provide an overview of challenges and opportunities of mm-wave communication in the the framework of 5G mobile broadband systems. More specifically, different challenges, i.e. drivers, spectrum, propagation channel, cost and energy efficient aspects, from the perspective of mm-wave communication are discussed. Furthermore, insights on research opportunities of mm-wave communication in heterogeneous networks and multi-antenna transceiver technologies are provided.

II. Drivers and Challenges of mm-Wave Communication in 5G Networks

By targeting a design of mm-wave communication for 5G networks, brings up multiple challenges to be faced. Addressing the challenges is of the utmost importance to

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design viable technology solutions for the next generation broadband networks. In this section, drivers and challenges are especially discussed from mm-wave communication perspective. These challenges can be categorized into several different groups, namely, spectrum aspects, propagation aspects, energy efficiency aspects, and cost aspects.

A. Drivers and Requirements

As discussed previously, a phenomenal growth in the volume of mobile traffic is envisioned due to proliferation of smart devices that support a wide range of new application and services. In the following, some of key drivers for mobile data traffic explosion in the next generation mobile broadband networks are provided [13][14]:

- Uniform user experience for all users across a 5G network; minimum 1Gbit/s data rate anywhere
- Support for ultra-high data rates up to 5 and 50 Gbit/s for high mobility and pedestrian users
- Support for real-time services; e.g. UHD/3D video streaming, tactile network, augmented reality, leading to stringent latency requirements, i.e. round-trip-time requirement to be 1 ms
- Support for cloud based services
- Support for proximity based services

By looking at above drivers, mm-wave communication looks a promising technology ground for further development and research in the framework of 5G networks.

B. Spectrum Aspects

Beyond the traditional sweetspot of spectrum for wireless communications which ends at around 6 GHz, there is an additional 200 GHz of spectrum in the so-called mm-Wave frequency range that today is mainly under-utilized. This spectrum band has channel sizes capable of supporting wireless data speeds of 10-50 Gbps. A significant proportion of this enormous radio spectrum could be unlocked within the next 5 years for 5G cellular and WiFi communications.

For the field of 5G research, the target is above 6 GHz, and the research in this field should look to electro magnetic field (EMF) aspects, link budgets, propagation issues, and channel model description. In the following, a low millimeter band and high millimeter bands within the range of 20 to 90 GHz are briefly discussed. Figure 1 depicts the low millimeter bands of interest in the 20-50 GHz range along with their currently allocated usage. As can be seen, a contiguous bandwidth up to 2 GHz can be found in this frequency range. It is worth noting that ITU co-primary service bands for mobile systems has been marked with green color. Currently, ITU co-primary mobile bands 20-50 GHz range have been used also for other services, e.g. fixed satellite services and navigation. Therefore, the co-existence of mm-wave communication with other existing systems needs to be carefully considered.

For higher part of mm-wave band, there is also 7GHz unlicensed spectrum surrounding 60GHz. Additionally, ITU has allocated lightly licensed 5GHz bandwidths for both 71-76 GHz and 81-86 GHz bands for establishing high bandwidth wireless links. Similarly, the band 92-95GHz has been allocated for high bandwidth wireless links,

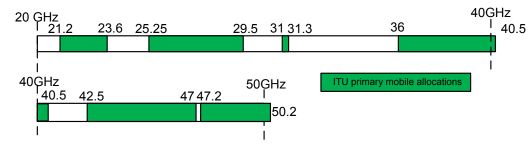

Fig. 1: Existing allocations for 20-50 GHz mm-wave spectrum with ITU co-primary mobile bands marked with green color.

C. Propagation Channel Aspects

Through understanding of radio channel is fundamental requirement to design efficient wireless solutions for next generation mobile broadband systems [1]. The characteristics of radio channel are reflected to the design of air interface and network architecture. Therefore, the need of accurate channel models play a key role while designing of future mobile broadband systems, supported by theoretical, simulation, and measurement efforts.

As discussed in previous section, due to availability of large contiguous chunk of spectrum, mm-wave bands around 30 GHz are attractive options for cellular communication in next generation mobile broadband systems. In contrast to the common understanding, various attenuation coming from atmospheric absorption, rain, fog or snow are not serious but even negligible in the case of frequency bands and the propagation distances of our interest. Of course, there is the additional path-loss in mm-wave frequency bands with respect to the frequency bands of conventional cellular systems. However, by exploiting antenna array either at the transmitter or the receiver the additional pathloss can be compensated [15].

D. Energy Efficiency and Cost Aspects

Recently, the large volume of research and development efforts in academia and industry have been dedicated for a green wireless communication in the fourth generation (4G) networks [16]. Clearly, in the context of 5G networks, the importance of green communication will become even more important with respect to existing systems. From a mm-wave communication perspective, novel energy efficient and cost-efficient multi-antenna transceiver architectures and mechanism to access large continuous chunks of spectrum are under interest. Additionally, the minimization of installation and operation costs of wireless backhaul are under high interests while deploying of scalable ultra-dense mm-wave small cell networks .

III. Research Opportunities of mm-Wave Communication in 5G Networks

This section addresses different research opportunities of mm-wave communication in the framework of next generation mobile broadband networks. Especially, different aspects of heterogenous networks as well as multi-antenna transceiver technologies are discussed.

A. Heterogenous Networks

Heterogeneous networks have been recognized as a paradigm shift in traditional cellular network deployment to enhance network capacity as well as service coverage area. In general, the elements of HetNet can be different type of network nodes equipped with different transmit power budgets, processing capabilities, and support for different radio access technologies (RAT)s. Hence, HetNets can be characterized as multi-hierarchical network with different overlaying layers. Figure 2 provides an illustration of HetNet deployment with mm-wave network elements. As can be seen, HetNet consists of mm-wave network nodes for access and backhaul and device-to-device (D2D) communication, as well as devices connected to other RATs than mm-wave.

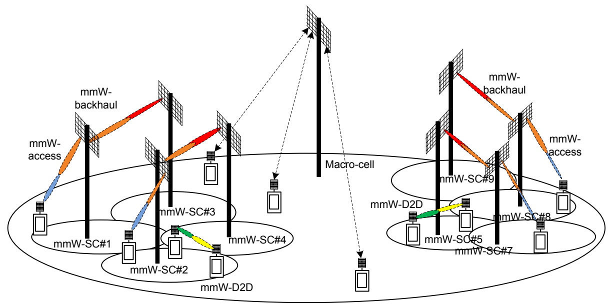

Fig. 2: An example deployment of HetNet with mm-Wave network elements.

1) Network Densification: A network densification is a prominent instrument to enhance network efficiency in terms of cells/km^2. In general, the performance enhancements can be obtained by deploying base stations/access points into a close proximity of a intended terminals/devices resulting in more favorable channel conditions between transmitters and receivers. Consequently, a reduced amount of transmission powers can be used leading to a reduced interference towards other co-existing network elements. Additionally, due to the extensive exploitation of large antenna arrays in mm-wave cellular communication, transmission and reception are by nature highly directive [1]. Hence, it can be expected that co-channel-interference between different mm-wave HetNet layers becomes reduced enabling mm-wave small layers to be ultra-densly deployed .

By enabling mm-wave devices to directionally communicate with each other in the proximity, traffic offloading from overlaying layers can be obtained. Therefore, device-to-device (D2D)/proximity communication can be seen as an integral part of network densification in 5G networks. Due to highly directive transmission and reception of mm-wave communication, it can be envisioned that the mm-wave D2D communication enables additional security as well as efficient leveraging of radio resources of overlaying network.

2) Backhauling: To provide uniform user experience across entire radio access network, the number of small cells may become large. Therefore, the backhaul solutions for 5G mobile broadband systems need to be more cost-efficient, scalable as well as easily installed with respect to traditional backhaul solutions. [17]

To enable ubiquitous ultra-high data rate and low latency mobile services under the coverage of 5G networks, backhaul transport has to provide a native support for this by enabling ultra-high capacity data transfer between access point and core-network. Traditionally, copper and fibre have been considered as cost efficient transport alternatives for locations with wired connectivity. However, for locations without wired connectivity, the building of wired transport may be an infeasible approach in terms of costs, i.e. maintenance (CAPEX) and operation (OPEX), as well as scalability. Therefore, there is a need to develop ultra-high capacity, low latency, and scalable as well as cost efficient wireless backhaul transport solutions for 5G mobile broadband networks.

To enable cost efficient deployment of scalable ultra-high capacity backhaul links with sufficient coverage, mm-wave radio at 20-50 GHz frequency range can provide an attractive alternative with respect existing technologies. Naturally, there are several research topics to be addressed for mm-wave technology based wireless backhauling, e.g. impact of backhaul network topologies, impact of mobility for backhauling, spectrum sharing between access and backhaul, and the impact of different duplexing schemes are under interest.

3) Co-existence of mm-wave with other HetNet Layers: To guarantee coexistence with other HetNet layer, potentially non mm-wave, efficient inter-working between different HetNet layers should be enabled. Therefore, there is a need to design coexistence methods for mm-wave communication to be integral part of overall 5G system.

B. Advanced Multi-Antenna Transceivers

To overcome unfavorable channel conditions in a cellular communication, i.e. pathloss in LOS/NLOS, signal blockage, by achieving high array gains, advanced beamforming techniques with large antenna arrays are required in mm-wave communications at both transmitter and receiver sides. By large antenna array, we mean that the number of antenna elements can be very large potentially up to hundereds [3].

One of the benefits for mm-wave technology is that large number of antenna elements can be packed into a small physical size leading a larger aperture and achieving to high antenna array gains [1].

Interestingly, in contrast to typical lower carrier frequencies, e.g below 6 GHz, spatial multiplexing gains are available even in LOS conditions at mm-wave bands [18]. In principal, spatial multiplex gains can be achieved by selecting antenna spacing properly with linear arrays leading to orthogonal eigenmodes [18]. Naturally, this generates a new interest dimension in mm-wave channel to be exploited in the next generation mobile broadband systems. Additionally, further research efforts are also required to take into account for mobility while designing transceivers for a mm-wave communication. Particularly, the impact higher velocities to different beam tracking algorithms need to be further studied.

1) Transceiver Architectures: To alleviate power consumptions, cost and implementation complexity problems in mm-wave communication, novel transceiver architectures are needed to realize multi-gigabit data rates in practical deployments.

Figure 3 shows a traditional digital spatial domain processing transceiver architecture. As can be seen, the most of the spatial domain signal processing is performed at baseband in discrete-time domain before digital-to-analog conversion

[1]Particularly, this holds in LOS conditions.

(DAC) or after analog-to-digital conversion (ADC). However, the power consumptions of the digital spatial domain processing architecture is substantially high. The reason for this is that large continuous transmission bandwidths associated with high sampling rates in ADC/DACs. Additionally, each transmit and receive antenna array elements is having dedicated DAC/ADC unit leading costs to be prohibitively high. It is worth noting that this architecture enables to control both the signal's phase and amplitude. Furthermore, the architecture is highly flexible and can provide support for data multiplexing, plain eigenbeamforming as well as operation in frequency selective channels.

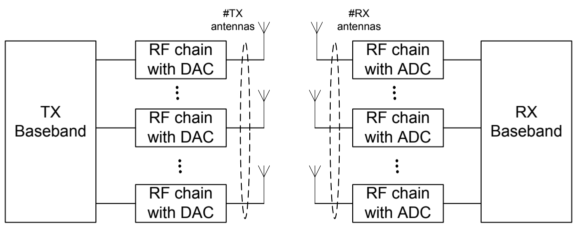

Fig. 3: Traditional digital spatial domain processing multi-antenna transceiver architecture.

An alternative transceiver architecture to reduce costs, complexity and power consumption is referred as analog beamforming with scalar complex weights [19]. In analog transceiver architecture, beamforming is shifted from a baseband to radio frequency (RF) front-end and phase shifters in beamformer are controlled digitally. In other words, an analog beamforming pattern is generated by quantized phases which control RF phase-shifter [20]. RF phase-shifters enable adaptive analog beam steering. Beamforming patterns can be formed by utilizing uniform linear array (ULA) or uniform planar arrays (UPA). However, due to scalar complex weights for the analog beamformer, it may face challenges for joint transmitter and receiver operation in frequency selective channels. Additionally, it is worth noting that only signal's phase information is controlled. Furthermore, this approach is targeted for single beam transmission but it is able extract spatial diversity and array gains of multi-antenna processing.

Figure 4 depicts an alternative hybrid analog-digital transceiver architecture for mm-wave communication. In hybrid analog-digital transceiver architecture, full spatial processing at RF frontend is to divide spatial processing on both RF-frontend and baseband processing units. The target of this hybrid multi-beam beamforming architecture is provide support for data multiplexing with reduced power consumptions and costs. Similarly to analog beamforming architecture, phase shifters in RF beamformers are controlled digitally to form narrow beams. The target of RF phase-shifters is to enable adaptive analog beam steering. The purpose of digital domain spatial processing is to perform actual precoding according to certain optimization criteria, e.g. zero-forcing, minimum mean square error (MMSE). To see further details on the architecture, an interested reader is advised to see details in [21].

Recently, the feasibility of mm-wave communication with adaptive beamforming transceivers has been successfully

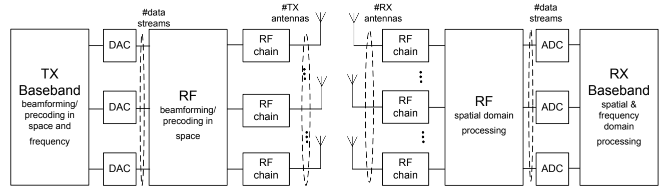

Fig. 4: Hybrid analog-digital multi-beam multi-antenna transceiver architecture for mm-wave communication.

demonstrated at 28 GHz carrier frequency with 500 MHz bandwidth [5]. The results show that mm-wave communication can support few-hunder-meter radius of outdoor and indoor coverage with more 500 Mbits/s with mobility up to 8km/h even in NLOS enviroment [5]. Additionally, in [22] a system-level performance of hybrid analog-digital transceivers by using multi-user MIMO transmission in multi-cell urban micro cell deployment with different antenna and user configurations has been evaluated. See Table 2 in [22] to find further details about the system-level simulation parameters.The system-level results demonstrate that hybrid analog-digital transceivers with built in multi-user support significantly enhance system-level performance metrics, e.g. average sector throughputs and cell-edge user's throughput, with respect to transceivers with a capability to support only single user.

IV. Conclusions

In this paper, we have provided an overview of research challenges and opportunities on mm-wave communication for 5G mobile broadband networks. More specifically, different challenges, i.e. use cases, service requirements, spectrum, propagation channel, cost and energy efficient aspects, from the perspective of mm-wave communication have been discussed. Furthermore, insights on research opportunities of mm-wave communication in heterogeneous networks and multi-antenna transceiver technologies have been provided. Based on provided overview, it can be concluded that mm-wave communication is a promising framework for further development and research towards next generation mobile broadband communication systems. Particularly, the leveraging of mm-wave communication on different hierarchical layers of HetNets is an inspiring framework for a future research.

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