Millimetre-Wave Air-Interface for 5G: Challenges and Design Principles

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Abstract—The extreme data rate requirements for 5G have pushed the mobile industry to exploit the large amount of available spectrum in the millimetre-wave (mm-wave) bands. mmMAGIC (Millimetre-Wave Based Mobile Radio Access Network for Fifth Generation Integrated Communications) is a European project aiming to develop novel radio access technologies for mobile communication at mm-wave frequencies. One of the main goals is the mm-wave air-interface design. In this paper, the key challenges for mm-wave air-interface design are first discussed. Afterwards, five key topics about air-interface are investigated in detailed regarding requirements/KPI’s and design principles. These five key topics are: Waveforms, channel codes and re-transmission schemes, frame structure and numerology, multiple access and duplexing schemes, and initial access schemes. The investigation in this paper not only provides insights into efficient design of mm-wave air-interface, but also help align various research activities in both industry and academia, paving the way for successful future 5G mobile communication networks.

Keywords— Millimeter wave, 5G, above 6 GHz, beyond 6 GHz, air-interface, radio interface, waveform, channel code, retransmission scheme, frame structure, numerology, multiple access, duplexing schemes, initial access

I. INTRODUCTION

The wireless traffic demand is growing extremely rapidly due to new services such as Ultra-High-Definition (UHD) Videos, Virtual Reality (VR) etc. A 1000-fold increase of the wireless traffic has been predicted [1]. The corresponding explosive growth of data rate demand for 5G and the “spectrum shortage” situation in the sub-6 GHz frequency range [2] have made it imperative for the mobile communications industry to explore millimetre-wave (mm-wave) bands. The mm-wave frequency bands (In contrast to the strict definition of 30-300 GHz, it is defined in this paper as frequency resources in 6-100 GHz) have much more available bandwidth than the legacy bands in sub-6 GHz range used today. They can therefore support much higher data rates and deliver demanding services in terms of capacity, throughput, latency, and reliability. In addition to large bandwidth, mm-wave has also the advantages of allowing small form factor implementation of large dimension antenna arrays and reduced interference due to extensive application of beamforming [3]. Thus, mm-wave technology is envisaged to be a core component of the 5G multi-RAT ecosystem.

mmMAGIC (Millimetre-Wave Based Mobile Radio Access Network for Fifth Generation Integrated Communications) [4] is a European project where research is performed on pivotal components aiming to develop novel radio access technologies for mobile communication in the frequency range 6-100 GHz. One of the key objectives in mmMAGIC is to design a novel mm-wave air interface that fulfils the key performance indicators (KPI’s) related to societal and operational 5G system requirements, such as user data rate in downlink (DL) and uplink (UL), connection density, traffic density in DL and UL, mobility, availability, reliability and latency, etc. However, the design of a mm-wave air interface is a challenging task. The propagation characteristics for communication over mm-wave frequencies differ quite a lot from those below 6 GHz. Furthermore, with increasing frequency, signals suffer severe hardware impairments, such as phase noise. In addition, the electronics become less energy efficient and the larger bandwidth leads to very high demand on signal processing capacity. Therefore, the success of the mm-wave air interface design relies on an efficient design that overcomes such specific challenges.

The mmMAGIC project has identified the main challenges, key requirements and design principles for mm-wave air interfaces to support a wide range of use cases, such as media on demand, dense urban society, smart office, moving hot spots etc. In this paper, five key topics of mm-wave air-interface design are investigated: waveforms, channel codes and re-transmission schemes, frame structure and numerology, multiple access and duplexing schemes, and initial access schemes. For each topic, the technological KPI’s and design principles are discussed, taking into account the the identified mm-wave specific challenges and extreme system requirements. The requirements and design principles will not only provide insights into efficient design of the mm-wave air-interface, but also help align various research activities in both industry and academia, paving the way for successful future 5G mobile communication networks.

This paper is organized as follows: Section II summarizes the key air-interface design challenges for mm-wave; Section III, IV, V, VI and VII describe the requirements/KPI’s and design requirements of the above mentioned five key topics, respectively. Section VIII concludes this paper and summarizes the future work.
II. KEY CHALLENGES FOR MM-WAVE AIR-INTERFACE

The mmMAGIC project identified a number of key challenges related to the deployment of mm-wave wireless communication systems.

The most obvious challenges arise from the propagation properties of mm-waves, since the free space path loss increases with the square of frequency, implying that the mm-wave transmissions above 30 GHz will experience higher path loss than transmissions in bands below 6 GHz. A compensation of such increased path loss is possible with increasing the antenna aperture to be comparable to that used in sub-6 GHz bands. However, this comes at cost of increased directivity of the antenna pattern, which in turn affects known air-interface design principles like usage of broadcast signals for channel estimation or link setup. Also interference characteristics look different, and the assumption of directive antenna pattern at transmitter and receiver impose more stringent accuracy requirements on beam steering and angle of departure and angle of arrival estimation.

In addition, recent channel measurement results in an urban outdoor scenario [5] and large indoor scenario [6] reveal a certain sparsity of the mm-wave channels with only few reflected paths with significantly smaller angular spread compared to sub-6 GHz channels. Here the challenge is to design beam steering algorithms finding the direction of the most dominant specular reflections and tracking them.

Since the penetration loss of mm-waves for usual wall materials is much higher than for sub-6 GHz frequencies, a mm-wave link is sensitive to blocking or shadowing effects. If a user blocks the signal path with his body or his hand this can significantly reduce receive power. Also outdoor to indoor coverage is difficult to achieve due to the higher penetration loss of most of the wall materials.

The most critical impact on the channel caused by mobility is the strong Doppler effect and, if high gain beams are used, a beam misalignment and thus resulting intermittent link quality.

Another number of challenges result from the non-ideal properties of real hardware realization of mm-wave transceiver components. This causes typical impairments like increased phase noise of the local oscillator, I/Q imbalance of the modulator/demodulator and baseband components. Also the sampling jitter and sampling frequency offset of the analog-to-digital converters, carrier frequency offset and nonlinearity of the power amplifier become relevant. These imperfections are present in every hardware implementation, but their impact in the mm-wave range is higher than in sub-6 GHz bands, because these hardware components are operated closer to the overall physical limits and therefore closer to the border of their capabilities related to operating frequency, bandwidth, transmit power and receiver sensitivity.

In particular, the power amplifier has lower efficiency at mm-wave frequencies, so that increased power consumption for a given transmit power target is expected.

The high signal bandwidth, associated with the substantially increased capacity expected from mm-wave transmission, causes additional challenges for the baseband processing. Sampling rate of ADC’s, processing time associated with channel coding, buffer requirements for re-transmissions, as well as low latency expectations promised by the high bandwidth, will have a significant impact on the transceiver design and complexity.

A further impact on the transceiver design comes from the hybrid beamforming architecture approach. This is seen as one potential solution to keep power consumption and hardware complexity reasonably low by using a reduced number of radio frequency (RF) chains in combination with hybrid analog and digital beamforming. This also may restrict the number of usable beamforming and Multiple-Input Multiple-Output (MIMO) schemes.

Due to practical realization reasons a non-symmetric antenna and RF configuration on the access point (AP) and user equipment (UE) is expected. Beam gain and transmit power at UE side will always be lower than on AP side, leading to an unbalanced link budget in downlink and uplink and potentially reducing uplink coverage. It is also difficult to design one air-interface to be applicable to the whole range of different deployment scenarios (indoor, outdoor, mixed indoor-outdoor).

Two basically different operation modes of the mm-wave system are considered currently, standalone and non-standalone operation. Whereas standalone mm-wave systems are intended to operate without support from other systems, the non-standalone systems make use of available connection with a mobile access system in the lower frequency bands, taking advantage from higher coverage and reliability for exchange of e.g. configuration and link setup information to support mm-wave link setup and operation. In consequence, different protocols and message exchanges for these two modes need to be foreseen. Further, since also self-backhaul should be supported as a solution to connect many access points in dense and ultra-dense deployments, flexible configuration of the air-interface is a challenging design target.

Finally, one of the most critical issues is the uncertainty of the frequency bands being made available by regulations in the future. The different frequency bands within the whole range of potential spectrum might require different approaches to address the described challenges. One reason is clearly that the technologies available to enable the targeted system approaches in a cost efficient way might be different, depending on the frequency band. Especially, if frequency bands should be used under shared conditions, this could cause additional burden on the air-interface design to ensure the coexistence.

Having the described challenges in mind, air-interface requirements/KPI’s and design principles will be derived in the subsequent sections, covering the key topics of waveform, channel code and retransmission schemes, frame structure and numerology, multiple access and duplexing schemes, and initial access schemes.
III. WAVEFORM DESIGN

The foundation of a successful mm-wave air-interface is based on the choice of waveforms. In general, waveforms are designed based on use cases requirements, propagation channel characteristics, transceiver complexity, spectral efficiency and hardware constraints, etc. In the past decades, a number of waveforms have been developed for wireless communications, each with its pros and cons. There is no single waveform that performs best in all scenarios and conditions. The 5G air-interface is envisaged to flexibly adapt its configuration (incl. waveform) to different use cases. Therefore, mmMAGIC is investigating a number of waveform candidates, including multi-carrier and single-carrier waveforms. The multi-carrier waveform candidates include Cyclic Prefix (CP)-OFDM, Windowed (W)-OFDM, Pulse-shaped (P)-OFDM [7], Unique-Word (UW)-OFDM [8][9], Universal-Filtered (UF)-OFDM [10], FBMC-Quadrature Amplitude Modulation (QAM) [11] and FBMC-Offset (O)-QAM [12]. The single carrier candidate waveforms are Discrete Fourier Transform-spread (DFT-s)-OFDM [13], Zero-Tail (ZT)-DFT-s-OFDM [14], Continuous-Phase-Modulation (CPM)-SC- Frequency Division Multiple Access (FDMA) as well as Differential (D)-QAM [15]. In the following, we provide requirements and main principles for the design of waveforms.

A. Requirements and KPI’s

In this paper, we define a number of KPI’s for the analysis of different waveform candidates for 5G mm-wave communications. These KPI’s are listed in the following:

- **Spectral efficiency** in order to fulﬁl extreme requirements on data rate, connection and traffic densities;
- **Good time localization** is required to enable low latency radio access to support extreme use cases. Moreover, for a time division duplexing (TDD) system, the demand for frequent link direction switching and the consequent need for short TDD guard times to allow switching sets demands on design of waveforms;
- **Peak-to-Average-Power-Ratio (PAPR):** Low PAPR can help increase effective transmit power and is required for users with critical link budget;
- **Compatibility with multi-antenna technologies (MIMO),** which is one of the key features driving mm-wave air-interface. The integration of beamforming/precoding/MIMO schemes has to be simple enough to meet the desired requirements;
- **Robustness against hardware impairments, especially phase noise,** since as mentioned in Section II, hardware impairments deteriorate at higher frequencies;
- **Computational complexity,** for the generation and decoding of information embedded in the waveform, to allow the usage of hardware chips with acceptable cost;
- **Flexibility,** in order to support diverse use cases, deployment scenarios, and wide-range of spectrum (6 - 100 GHz);
- **Out-of-band emissions:** to support potential co-existence of different services in frequency domain;
- **Robustness to frequency/time selective channel, since for large bandwidths the channel is expected to be highly frequency selective in nature. However, if under narrow beams, the effective channel may have reduced frequency selectivity. Furthermore, due to strong Doppler effect, mobile users have channels with higher time-selectivity;
- **Impact to the link budget, some waveforms with mismatched transmit and receive filter pair may lead to a considerable power loss.**

B. Design principles

According to the above KPI’s, five design principles of waveform design can be summarized as follows:

- **Exploit mm-wave channel/link characteristics,** such as sparsity of multipath components, high directivity, large bandwidth, and spatial correlation. Moreover, different channel characteristics in different deployment scenarios e.g., indoor, outdoor, mixed indoor/outdoor, should be taken into account;
- **Exploit the extensive use of beamforming/precoding/MIMO schemes.** For waveform design, the effective channel is more relevant than the propagation channel. Since beamforming/precoding changes the effective channel e.g., number of paths and frequency selectivity, the waveform design should consider different possible beamforming/precoding schemes that lead to different characteristics of the effective channel;
- **Use the established KPIs in Section III.A, to analyze, compare, and optimize the waveforms;**
- **Use realistic models in evaluation.** These models include channel propagation models and RF/hardware impairment models at both transmitters and receivers;
- **Aim at a flexible and adjustable waveform design, in order to support wide range of requirements for a wide range of frequencies and deployment scenarios (e.g., indoor/outdoor) and different channel conditions (e.g. LOS/NLOS).** One possibility is to enable a multi-mode air-interface, where possibly different waveforms (or the same waveform with different numerology) can be used in different conditions and scenarios.

Based on the above KPI’s and design principles, the waveform candidates listed in this section will be investigated and evaluated regarding their applicability for mm-wave communication systems. Here, we briefly describe the possible research directions.

OFDM with additional windowing/pulse shaping is a common implementation in practice, to balance the time-frequency smoothness of OFDM signals and reduce the out-of-band emission. However, the exact window/pulse shaping design remains open for mm-wave systems. For W-OFDM, different methods for maintaining orthogonality between subcarriers while minimizing the overhead (e.g., increased CP) and suppressing the out-of-band emission will also be investigated.
For P-OFDM, optimum pulse shape design will be investigated taking into account different time-frequency densities, SNR enhancement, phase noise robustness, adaptation to channel characteristic regarding time- and frequency selectivity, robustness to synchronization error etc.

For UW-OFDM, efficient schemes will be developed where the UW is used for synchronization, channel tracking and/or RF impairment compensation purposes. In this way, the original overhead (time and power) spent for CP is used for transmitting know sequences like UW that can help to improve performance.

For UF-OFDM, the advantages for data transmission compared to CP-OFDM will be investigated. UF-OFDM has shown to provide advantageous characteristics for the transmission of data in frequency regions below 6 GHz. It will be investigated if these advantages translate into frequency regions above 6 GHz taking the respective design choices of the project into account (e.g. spacing, frame design etc.).

For FBMC with QAM or OQAM signaling, time-frequency analysis will be conducted considering bi-orthogonal or orthogonal designs, aiming to achieve improvement compared to CP-OFDM waveform regarding power efficiency in the sense of time-frequency oversampling loss, energy efficiency in sense of mismatched filtering loss, time-frequency localization property for combating Doppler spread, synchronization error and phase noise. Compared to FBMC-OQAM, the application of MIMO and channel estimation in FBMC-QAM is straightforward and similar as OFDM. The compatibility and the performance under beamforming/precoding/MIMO schemes will be investigated.

IV. CHANNEL CODES AND RE-TRANSMISSION SCHEMES

Most of today’s Forward Error Correction (FEC) mechanisms rely on graph-based codes, notable examples of which are Low Density Parity Check codes (LDPC, used e.g. in 802.11n/ac/11ad and 802.15.3c), and Turbo codes (used in UMTS and LTE). Both are decoded by means of soft-decision iterative decoders. While Turbo codes are not proven to achieve capacity for any type of channel (because of the inherent error floor appearing at high SNR values), they are well studied and perform very well for shorter block lengths. In contrast, spatially coupled LDPC codes [16] and Polar codes [17] are known to achieve capacity of symmetric memoryless channels, the latter being still under research in order to improve their finite length performance. High throughput mm-wave systems can therefore consider any of Turbo codes, LDPC codes and/or Polar codes as suitable candidates for channel coding mechanisms.

A. Requirements and KPI’s

High data rates and ultra-low latency requirements are foreseen in mmMAGIC. The KPIs related to the design of channel codes for mm-wave bands can thus be enumerated as follows: throughput, throughput per hardware resource unit (e.g. per chip area), latency, error correction capability, complexity, power consumption, memory consumption and suitability to re-transmission schemes. For the use cases where latency is of paramount importance, e.g. tactile Internet, low computational complexity is needed to shorten the latency. On the contrary, for the use cases targeting at extremely high user data rate, e.g., smart offices, spectral efficiency should be prioritized and longer block length and high computational complexity are affordable since latency can be up to 10 ms.

The extremely high data rates required for the use cases put challenges on the design of re-transmission protocols. mmMAGIC will thus investigate and devise retransmission protocols (e.g., HARQ, ARQ, and the associated recent advancements [18]) in order to support reliable communication together with the channel code employed for forward error correction. The extremely high data rate and low latency use case KPIs ask for the following key performance indicators: Latency, complexity, reliability, suitability to forward error correction (channel code design) and flexible round trip time. Since data rate is assumed to be very high, the processing delay of advanced HARQ may cause longer delays than retransmission and soft combining. That is, the delay incurred by complex ARQ/HARQ schemes may be longer than a simple retransmission. Hence complexity and latency are expected to be the major design requirements, also leading to the ability to have flexible values of the HARQ round trip time (HARQ RTT).

B. Design principles

Among the general design principles for channel codes, the following ones can be highlighted in light of the peculiarities of mm-wave systems:

- Performance of channel codes should be evaluated according mostly to those KPIs that are relevant to mm-wave systems (cf. Section III.A).
- Different block lengths and code rates should be studied in each case, given the very wide bandwidth options that are foreseeable in mm-wave bands.
- Because of the ultra-high data rates that are achievable in these systems, reducing the encoding/decoding complexity should receive careful consideration.
- Channel code designs should be flexible enough to perform well under different use cases and scenarios, sometimes requiring the development of novel coding schemes with current Turbo, LDPC and Polar codes as a baseline for further research.

Retransmission schemes are on the other hand closely related to channel codes. An important distinction in mm-wave systems is that, given the ultra-high achievable data rates, the processing delay of advanced ARQ/HARQ schemes may be comparable or even longer than the cost of channel usage. Thus an important question to ask is whether ARQ/HARQ should be used at all or not, although this can only be answered on a per use case basis. For example, there may be use cases where stringent reliability and availability requirements demand particularly robust links against channel impairments, which can only be achieved with the use of retransmissions and the
correspondingly low residual error rates. In other cases retransmissions might be dispensable. This analysis should be conducted prior to exploring further advances in retransmissions for mm-wave systems.

In general, the following design principles can be highlighted for retransmission schemes:

- Assess in each use case whether retransmissions are needed or not.
- Develop new ARQ/HARQ concepts with tight limits on complexity and latency.
- Investigate the impact of higher layers on retransmission delays.
- Explore fast retransmission schemes prior to decoding or under partial FEC decoding mechanisms.

If present, ARQ/HARQ obviously relies on channel decoding. Any developments in retransmission methods therefore need to be aligned with the developments in FEC codes. As an exception to this, early detection of packet errors prior to channel decoding can be useful when very large packets are sent over short periods of time, in order to decouple retransmissions from channel decoding. This can be of particular importance in centralized deployments where significant part of the delay budget is spent at the transport network, thus making it challenging to meet stringent HARQ round trip time requirements.

V. FRAME STRUCTURE AND NUMEROLOGY

A. Requirements and KPI's

Existing frame structures (LTE-A and 802.11) are not necessarily well optimized for higher frequencies and larger bandwidths.

Due to high carrier frequency, Doppler spread has more detrimental effect, and phase noise and other hardware impairments cause higher loss. Numerology, e.g. subcarrier spacing, has to be designed so that the performance is adequate.

To realize the high target data rates, the system bandwidths can be very large, e.g. up to several GHz. The frame structure should be able to handle any bandwidth, including large ones and small ones. Furthermore, large bandwidth corresponds to high processing demand. Thus, frame structure and numerology need to allow low complexity transceiver implementation.

Properly designed frame structure is the main enabler for low latency. For this purpose, subframes have to be short enough, while the control information must be transmitted in sufficiently small periods. Low latency has beneficial effect on the receiver complexity and HARQ buffer sizes, even though it is not required by all applications.

Massive MIMO and beamforming are challenging from the control channel and demodulation reference sequence (DMRS) design point of view. Control channel structures should enable good control coverage in all situations. DMRS overhead should be kept small enough, but at the same time low loss channel estimation should be enabled.

The air interface has to support both standalone and non-standalone operation, and with TDD, frame structure has to provide support for cross-link interference mitigation.

Energy and power efficiency are important features in 5G mm-wave systems. The frame structure has to support energy saving in both AP and UE. Fast transitions between sleep and active modes, and short active times can be enabled by properly designed multiplexing of control and data.

Finally, to ensure 5G systems applicability to all situations and environments, the frame structure and numerology have to be scalable and flexible. Requirements have to be met in LOS/NLOS channels, in access and backhaul links, different carrier frequencies, system bandwidths, and massive MIMO configurations. Frame structure has to support for any transceiver architecture.

B. Design principles

Based on the above requirements and KPI’s, state-of-the-art frame structure and numerology designs, such as LTE-A [19], 802.11ad and some new proposals in the literature [20][21], will be analyzed, assessed and further developed, by taking into account higher Doppler spread, stronger phase noise and the large amount of available bandwidth. Further aspects include the flexible operation with different bandwidths and on different carrier frequencies, efficient synchronization, initial access, channel estimation, beamforming and beam tracking. Special attention must be given to advanced receivers in the case of massive MIMO and multi-node schemes, i.e. the frame structure should be agnostic with regards to transceiver architecture and algorithm implementation.

For seamless support for both standalone and non-standalone systems, different requirements for control channels, reference sequences and guard times will be investigated. For example, in non-standalone system, initial access can be done with lower frequencies, and these resources can be freed to data transmission, thus reducing overhead. In standalone system, adequate coverage must be guaranteed by proper design of random access channel (RACH) and downlink common control channels. Dynamic spectrum sharing and inter-working should be enabled by both modes.

For the stand-alone system, beamforming for common control is a design challenge. In particular, the design of broadcast channel must enable sufficient coverage for common control information. The main challenge is that without channel knowledge, UE specific beamforming cannot be used.

Furthermore, frame structure and numerology should provide the flexibility and scalability to adapt to different bandwidths, carrier frequencies, link types (access/backhaul/D2D/V2X), and subframe/TTI duration. In certain cases we may also want to use adaptive TTI length, which is typically a multiple of the subframe length.

An important practical consideration is the sampling clock frequency. Preferably, it should be a power-of-two multiple of
the LTE clock, but integer multiple and fractional multiple would give more freedom in numerology design.

All of the above aspects should take into account the overhead. Proper ratio between data and control resources and dimensioning of guard period and cyclic prefix ensure good performance with reasonable overhead. Several trade-offs have to be taken into account, such as between latency and overhead.

The investigations of frame structure and numerology design can be summarized as following:

- Subcarrier spacing in the case of OFDM and single carrier. Optimization has to be done over phase noise, overhead, and Doppler;
- CP length, also in the case of OFDM and single carrier, has to be dimensioned so that it covers most of the delay spread in typical channels;
- Subframe length, which affects achievable latency and overhead;
- Position and structure of control channels: Latency, overhead and massive MIMO considerations have to be taken into account;
- DMRS position and structure: properly designed DMRS can greatly improve latency and improve channel estimation accuracy. Separate reference symbols for Doppler, phase noise and carrier offset tracking may be needed (multiplexed with data);
- Guard period: In TDD systems a guard period is needed for direction switching. It should be dimensioned so that it covers hardware switching time and propagation delay;
- Discontinuous transmission: In certain applications, properly functioning DTX (and DRX) can greatly improve battery life. This should be supported by the frame structure.

VI. MULTIPLE ACCESS AND DUPLEXING SCHEMES

A. Requirements and KPI’s

Efficient multiple access schemes will allow an efficient use of the available communication resources (time, frequency, code and space) when serving multiple users with different requirements. As the data rate requirements for the UL and DL may vary depending on the use case and, consequently, may be of different range from symmetric to very asymmetric, flexible duplexing schemes are needed to efficiently support such a dynamic range of UL and DL data traffic requirements.

The use of mm-wave technologies allows antenna arrays with a very large number of elements at both the transmitter and receiver. This opens up dimension in space which could be exploited for spatial multiplexing and (multi-user) beamforming for data transmission. Antenna arrays with different antenna gain and beam-width as well as different antenna array architectures can be envisioned. Hence, MIMO technique should also be incorporated when considering the multi-access design at mm-wave. A key aspect is how to maximize the efficiency under constraints of hybrid beamforming architecture having a limited number of RF chains/digital paths [3].

Candidate solutions for multiple access and duplexing schemes need to provide support for different antenna array configurations and hardware architecture. For instance, the AP’s may be equipped with much higher number of antenna elements and RF chains than the UEs, the beam width in DL may typically be narrower than in the UL. Moreover, the schemes have to be robust to deficiencies in the implementation, e.g., PHY layer imperfections due to channel estimation and/or phase synchronization errors, which may produce interference to other users, and also robust to human blockage while allowing mobility of users.

Candidate solutions for multiple access schemes should exploit context-aware information in the protocol design, such as when and where the user is at any given time. Considering the UL/DL traffic asymmetry and the various UL/DL data rate requirements in many use cases, the duplexing scheme should support flexible traffic in UL and DL. Furthermore, it is very important to design multiple access and duplexing schemes that support both backhaul and access transmissions. Since the backhaul transmission will be done between two or more AP’s, cross AP coordination of the multiple access scheme is required. Sharing of frequencies between backhaul and access, or in-band backhaul, may need to be considered – giving rise to possible scheduling complexities.

In summary, the following KPI’s should be considered for the design of multiple access and duplexing schemes:

- Data rate
- Connection density
- Latency
- Flexible scheduling
- Scheduling complexity
- Resource usage efficiency
- Robustness to PHY imperfections
- Availability and accuracy of context information

B. Design principles

As a result of the unique characteristics of mm-wave propagation, existing multiple access schemes for cellular systems have to be largely revised and new approaches introduced to efficiently use the available communication resources in all the possible dimensions (time, frequency, code and space).

Due to the limited power available at the UE, some initial simulation studies have already shown that FDMA best suits the uplink by allowing several UEs to transmit at maximum power on different bands [22]. Enabling FDMA (within a TDD time slot) can have benefits in terms of more efficient transmission for small packets, reduced UE power consumption and increased UL system capacity. In fact, having only one UE transmitting or receiving in a time slot (e.g., TDMA) is extremely wasteful for small packets. However, when having hybrid beamforming architecture [3], frequency-selective beamforming may not be possible, causing difficulty in serving multiple UE’s via FDMA. Among other access
schemes, spatial-division multiple access (SDMA) could be utilized along with temporal or frequency-based multiple-access techniques to greatly increase capacity and spectrum reuse.

The problem of inter-cell interference, which afflicts dense heterogeneous network deployments, would be significantly reduced with the use of highly directional steerable beam antenna arrays at the UE and/or AP [5]. Controlling the beamwidth to reduce the interference in contention-based access schemes has been studied in [23]. In [24], a codebook-based beamforming protocol is introduced at MAC layer in a distributive manner to determine the beam sets. The proposed protocol can reduce the total setup time, increase the system throughput and improve the energy efficiency. In [23], an algorithm to determine the beamwidth of quasi-omni-directional (QO) antenna pattern levels during contention-based channel access in mm-waves is proposed and it allocates the beamwidth of each QO level in an adaptive fashion in order to maximize the channel utilization and satisfy link-budget requirements.

The user body, other pedestrians, and other obstacles can block connections to a user. The blocking pedestrian has to be in a small region near the user to potentially block the path from the AP to the user. However, the impact is potentially much higher with groups of moving pedestrians [25]. These types of blockage will have to be addressed by either switching to another reflection path or connecting to another AP. Hence it is critical to maintain a rich path inventory for each user by continuously tracking both LOS and various reflection paths.

Relay selection can be applied to increase the spatial reuse and thus improve the network performance [26]. The blockage robust and efficient directional MAC protocol (BRDMAC) introduced in [26] computes both the near-optimal relay selection to maximize spatial reuse, and near-optimal schedules with respect to the total transmission time, respectively. Coordination in the uplink among stations can also bring benefits by establishing two-hops links of high channel quality [27].

VII. INITIAL ACCESS SCHEMES

A. Requirements and KPI’s

Due to the severe path attenuation of mm-wave signals, it is challenging for the conventional design of initial access procedures to achieve required coverage. This is originated by the fact that initial access schemes such as the cell search and RACH are based on broadcast signals. Therefore, the initial cell search and the random access procedure need to be designed properly to exploit the diversity in the time/frequency domain and possibly the spatial dimension as well.

It is a usual assumption that mm-wave systems could rely on sub-6 GHz technologies, such as the traditional 4G macro AP, for initial access procedures. However this assumption precludes standalone operation of mm-wave systems. It is therefore important to investigate initial access schemes which remain applicable for standalone operation, where we envision that fast beam-finding and -tracking may need to be supported for control tasks.

For standalone operation, the feasibility of beamforming during initial access is hindered by the fact that the direction of the best beam is a-priori unknown for initial access. This problem is further exacerbated in those scenarios where the UE is characterized by high mobility. On the other hand, not exploiting beamforming would lead to reduced access coverage and increased interference, especially for use case requiring high connection density. Coupling beamforming with initial access is therefore of great importance for standalone mm-wave systems and demand specific research on this area.

For non-standalone operation, the use of available information at the AP and UE (e.g. locations, UE ID’s, etc.) could help reduce the delay of initial access, if a connection on a sub-6 GHz band already exists. Fast re-connection to AP’s in presence of body blockage could be achieved using sub-6 GHz band.

An important key parameter in designing efficient initial access schemes is the delay occurring between the time of UE being switched on and its completion of establishing a Radio Resource Control (RRC) connection with the network and the overall communication overhead. In addition to delay, another performance indicator of the designed initial access is the so-called access ratio. It is the percentage of UE positions in a mm-wave cell that can have successful access to the mm-wave AP (cell/AP detection + association). Moreover, initial access in the context of high mobility needs also to be considered.

Candidate solutions for initial access schemes should be inherently flexible. First, the initial access schemes should support both standalone mm-wave network and overlay mm-wave network. Second, it should be transceiver architecture agnostic, i.e., support both transceivers with symmetric (shared antenna for Tx and Rx) and asymmetric antenna (separate antennas for Tx and Rx) configurations.

In the following, KPIs for the design of initial access schemes for mm-wave RAT are summarized:

- Access delay
- Access ratio
- Overhead
- Complexity
- Availability and accuracy of context information
- Standalone/non-standalone operations support
- Antenna configurations support

B. Design principles

To achieve the above design objectives, novel initial access procedures such as cell search and random access channel (RACH) are deemed necessary.

In [28], an exhaustive series of indoor measurements using a software-radio platform are conducted. Among the several insights raised up by the measurement study, it is found that the beam-searching algorithm proposed by the IEEE 802.11ad standard costs more channel occupancy than the Gb/s data transmission, and thus degrades severely the overall throughput. It is also discovered experimentally that 802.11ad
links tend to be asymmetric and that the effectiveness of beam searching is sensitive to blockage position, device motion, and reflectivity of environment. Finally, the presented measurements demonstrate that even super-narrow beams can leak signals causing interference and poor spatial reuse. A further drawback of 802.11ad is that only the case of single RF chain per antenna array is assumed.

If the control signalling can run over the lower frequency system (e.g. Macro cell), the initial access schemes may be drastically simplified. Correspondingly, the UE access delay may be significantly reduced and the access ratio can be considerably increased.

A multi-stage/tree-based method is proposed in [29] to reduce beam finding period compared to linear sweeping. Synchronization signals are transmitted with beams having decreasing beam width, i.e., in the first stage a wide beam width is used, while in the next stage a more narrow beam width is used, and so on. The receiver feeds back information for each stage about the best received beam and the transmitter can then reconstruct the beam direction and thereby select an appropriate range of beams for the next stage. It is shown that the setup time is significantly reduced, as little as 2% of the exhaustive searching protocol.

A codebook-based beamforming protocol at medium access control (MAC) layer is then introduced in a distributive manner to determine the beam sets. Considering codebook-based beamforming, [30] develops reduced complexity algorithms for optimizing the choice of beamforming directions, premised on the sparse multipath structure of the mm-wave channel. Specifically, the cardinality of the joint beamforming search space is reduced, by restricting attention to a small set of dominant candidate directions. The results show that the proposed schemes enable a drastic reduction of the optimization search space (a factor of 100 reduction) with negligible loss compared to the optimal performance.

Compressive beam tracking/finding was proposed in [31], which transmits pseudo-random pilot sequences in random directions and uses compressive sensing techniques at receiver. Very few works have investigated initial access schemes for hybrid beamforming architectures. Among them, [32] developed an adaptive algorithm in order to estimate the mm-wave channel, angle of departure and angle of arrival.

VIII. CONCLUSIONS AND FUTURE WORKS

In this paper, a number of mm-wave specific challenges for air-interface design have been summarized, including high free space loss and directional transmission, different channel characteristics compared to sub-6 GHz channels, vulnerability to blocking/shadowing, channel under mobility (causing strong Doppler effect, beam misalignment and intermittent link quality), hardware impairments (including phase noise, I/Q imbalance, nonlinearity etc.), reduced efficiency of the PA and increased power consumption, much larger bandwidth, hybrid transceiver architecture with both analog and digital processing, non-symmetric antenna and RF configuration between AP and UE, mixture of standalone and non-standalone deployments, support of both access and backhaul operations, and uncertainty of the frequency band.

Taking into account the above challenges, the requirements/KPI’s and design principles for five topic are summarized as follows:

- **Waveform**: The identified KPI’s include spectral efficiency, time-localization, PAPR, MIMO compatibility, robustness against RF impairments (especially phase noise), complexity, flexibility, out-of-band emissions, robustness to frequency- and time selectivity of channels. The waveform should be designed taking into account mm-wave channel characteristics, multi-antenna techniques, transceiver characteristics, flexibility and scalability. A number of multi-carrier and single carrier waveforms have been identified as candidates, including CP-OFDM, W/P-OFDM, UW-OFDM, UF-OFDM, FBMC-OQAM/QAM, DFT-s-OFDM, zero-tail DFT-s-OFDM, CPM-SC-FDMA, eeCPM-SC and DQAM-SC. As future work, such candidate waveforms will be assessed based on the above KPI’s and using realistic channel- and impairment models. A flexible and scalable waveform solution will be developed to cover wide range of scenarios, use cases, and spectrum;

- **Channel code and re-transmission schemes**: The main requirements are to fulfill very high throughput and a wide range of latency requirements. Due to large bandwidth, capacity achieving codes, such as LDPC, spatially coupled LDPC, and Polar codes, etc., can be used. However, due to extremely high throughput, code complexity reduction becomes the major KPI. Further KPI’s include latency, throughput, throughput/chip area, latency, error correction capability, and power/memory consumption. Moreover, the necessity of re-transmission should be assessed on a per use case basis. When needed, re-transmission schemes should fulfill KPI’s in terms of latency, complexity, and reliability. As future work, candidate channel codes will be evaluated regarding the above mentioned KPI’s. Low complex decoding techniques will be explored. Furthermore, re-transmission mechanisms based on early error detection will be investigated. Both designs of channel code and re-transmission will be kept mutually aligned;

- **Frame structure and numerology**: The wide contiguous bandwidths, high carrier frequencies, certain hardware impairments (e.g. phase noise) have to be taken into account, with the aim to fulfill high data rate and low latency. Large number of antenna elements need to be supported, calling for scalable air interface. To allow enhanced energy efficiency, DTX and DRX should also be supported. Adaptability and re-configurability are important due to diverse deployment scenarios and different link types. Several different transceiver architectures should be supported seamlessly. As future work, most advanced frame structure candidates will be studied, evaluated and extended for mm-wave RAT, taking into account the mm-wave specific challenges. The
aim is to achieve the user experience related targets, reduce complexity, enhance energy efficiency, allow adaptability and re-configurability by developing a scalable frame structure that is agnostic to transceiver architecture:

- **Multiple access and duplexing schemes**: Multiple access schemes should ensure efficient use of the available communication resources (time, frequency, code and/or space), while duplexing schemes should allow dynamic matching of UL and DL traffic requirements. Both should take into account the extensive use of antenna arrays, support different antenna array configuration and transceiver architecture, and imperfections in PHY implementation. The design should exploit context-aware information and relay selection to improve the network performance. As future work, multiple-access concepts will be developed for access and backhaul communication in different use cases and deployment scenarios, utilizing a mixture between SDMA and TDMA/FDMA/CDMA, exploiting context-aware algorithms and considering PHY imperfections. Analysis of TDD and FDD schemes will be carried out taking into account massive arrays and high UL/DL traffic dynamics.

- **Initial access schemes**: The key KPI’s include the access delay (between user request and completion of initial access), and the overall communication overhead. Both stand-alone and overlay mm-wave networks should be considered. PHY imperfections play an important role in the design. Accordingly, two strategies can be applied: i) Consider some imperfections in the design; ii) Transparent design to such imperfections. Furthermore, initial access should be coupled with beamforming and should exploit contextual information of UE’s. As future work, initial access mechanism will be designed considering highly directional transmissions, mobility, practical uplink constraints, existence of multiple neighboring AP’s, sub-6 GHz macro coverage and different options of transceiver architectures, making use of advanced compressive sensing techniques and context-learning algorithms.

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