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Dependable wireless connectivity: insights and methods for 5G and beyond

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Dependability is a measure of availability and reliability of systems/services. In the context of communication systems, dependability is governed by the coverage probability of the network under prescribed service requirements, by the latency of data transmissions as well as by the transmission error probability. Achieving dependable connectivity can be very challenging, especially within wireless mobile communications, where the transmission channel is often prone to severe fading and strong interference. Current generations of cellular mobile communication systems (4G and below) can mainly provide best effort services and are not well equipped to achieve a sufficiently high level of dependability as required by many novel applications, such as, road-safety relevant information exchange in vehicular communications, as well as, wireless remote operation of robots and drones. Standardization bodies have already recognized the market potential of such use-cases for mobile communications, and correspondingly efforts are ongoing to enhance the fifth generation of cellular systems (5G) towards ultra-reliable low-latency transmission. In this paper, we provide insights gained by our research work within the *Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion* with respect to factors influencing the dependability of 5G mobile cellular systems, and we present our achievements over the past two years for enhancing the robustness, reliability and efficiency of dependable wireless communications.

Keywords: massive MIMO; millimeter wave; multicarrier transmission; dynamic radio network architecture; vehicular communications

Zuverlässige drahtlose Konnektivität: Erkenntnisse und Methoden für 5G und seine Nachfolger.

Die Zuverlässigkeit (Engl. dependability) eines Systems oder eines Dienstes ist ein Maß für dessen Verfügbarkeit und Ausfallsicherheit (Engl. reliability). In Mobilfunksystemen wird Zuverlässigkeit hauptsächlich durch die Netzabdeckung für vorgegebene Servicanforderungen bestimmt sowie durch die Fehlerwahrscheinlichkeit und die Latenzzeit der Datenübertragung. Zuverlässigkeit drahtloser Verbindungen zu gewährleisten, stellt eine große Herausforderung dar, da grundlegende physikalische Eigenschaften des drahtlosen Übertragungsmediums, wie Kanalschwunderscheinungen und Interferenzen, inhärente Beeinträchtigungen verursachen. Aktuelle Generationen von Mobilfunksystemen (4G und seine Vorgänger) bieten vorwiegend sogenannte "best effort" Dienste an und sind nicht ursprünglich dafür geschaffen, Anwendungen mit strikten Zuverlässigkeitsanforderungen hinreichend sicher zu unterstützen. Neuartige Anwendung von drahtlosen Übertragungssystemen, wie zum Beispiel der Austausch verkehrssicherheitsrelevanter Informationen in der Fahrzeugkommunikation oder die drahtlose Steuerung von Robotern und Drohnen, verlangen jedoch nach einem sehr hohen Grad an Zuverlässigkeit. Das Marktpotential solcher Anwendungen wurde bereits von Standardisierungsgremien erkannt, und entsprechende Weiterentwicklungen von Mobilfunksystemen der fünften Generation (5G) in Richtung sehr geringer Latenzzeiten und hoher Ausfallsicherheit sind derzeit in vollem Gange. In unserer Forschungsarbeit im Christian Doppler Labor für Zuverlässige Drahtlose Konnektivität für eine Gesellschaft in Bewegung erforschen und entwickeln wir Methoden, um die Zuverlässigkeit von Mobilfunksystemen zu verbessern. Mit dem vorliegenden Artikel geben wir einen Überblick über unsere Erkenntnisse und die daraus resultierenden Weiterentwicklungen von Mobilfunktechnologien.

Schlüsselwörter: Massive MIMO; Millimeterwellen; Mehrträger-Modulation; dynamische Funknetzarchitektur; Fahrzeugkommunikation

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1. Introduction

The currently ongoing standardization of fifth generation (5G) wireless communications puts dedicated effort into enhancing the reliability and reducing the latency of mobile wireless communications within the Third Generation Partnership Project (3GPP) work task on ultra reliable low latency communications (URLLC) [1, 2]. This URLLC work task is closely related to enabling dependable wireless communications. Dependability is a measure of availability and reliability of systems/services. In the context of communication systems, dependability is therefore governed by the coverage probability (or equivalently the outage probability) of the network under prescribed service requirements, by the latency of data transmissions as well as by the transmission error probability.

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The 5G mobile wireless communications standard will bring along a host of new technologies ranging from physical layer (PHY) up to the network layer (NET). 5G will see significant extensions of carrier frequencies from several hundred MHz up to tens of GHz into the so-called millimeter wave (mmWave) regime [4]. The number of active antenna elements supported by base stations (BSs) will substantially increase to enable three-dimensional beamforming with a high-degree of spatial multi-user multiplexing [5]. BSs will extensively feature spatially distributed active antenna systems to enhance macro-diversity of connections, to reduce the access distance of users, and to improve the coverage of the network [6]. Furthermore, centralized processing of transmit/receive signals on servers in the cloud, in so-called cloud radio access networks (CRANs), will enable significant gains in network capacity and energy efficiency [7], whereas localized edge processing [8] of signals and direct communication between devices [9] will support low latency transmissions. Thus, 5G will be characterized by large heterogeneity of PHY technologies, access modes and network architectures, requiring very high flexibility and adaptability of the communication standard to effectively support various use-cases and application scenarios [10].

In this paper, we discuss several enhancements of 5G technologies towards availability and reliable transmission to support dependable wireless connectivity. In Sect. 2, we discuss issues relating to massive multiple-input multiple-output (MIMO)/full-dimension MIMO (FD-MIMO) systems w.r.t. uncertainty of channel state information (CSI) at the transmitter (CSIT) and antenna array geometry/deployment. In Sect. 3, we investigate the potential of flexible numerology to enhance the robustness of multicarrier transmission. Finally, in Sect. 4 we discuss improvements of the NET, specifically dynamic distributed antenna systems (dDASs) as a potential CRAN implementation, and device to device (D2D) relaying in the context of vehicular communications.

2. Full-dimension MIMO beamforming

FD-MIMO refers to wireless transmission systems that support two-dimensional antenna arrays with a large number of active antenna elements [11, 12]. This enables high-resolution beamforming in the elevation and the azimuth domain, in order to achieve large spatial multiplexing gains by serving many users in parallel. It also allows to enhance the energy efficiency of wireless data transmission by concentrating the radiated energy towards intended users. FD-MIMO is furthermore an enabler for utilizing mmWaves in mobile communications, since it allows to overcome the large pathloss associated to mmWave transmissions [13]. Initial realizations of FD-MIMO have already been standardized in long term evolution (LTE) release 13; yet, further improvements are still ongoing within 3GPP standardization. Theoretical results on FD-MIMO and massive MIMO systems promise order of magnitude spectral efficiency gains through high-degree spatial multiplexing under the assumptions that the transmitters are well informed about the current channel state and that users experience so-called favorable channel conditions [14]. The former assumption is hard to justify in high-mobility situations, where channel state information (CSI) varies quickly over time; we summarize below in Sect. 2.1 our insights on robust beamforming under CSI uncertainty at the transmitter. The validity of the latter assumption of favorable channel conditions is not immediately justified under practical circumstances and requires detailed consideration of antenna array geometry/deployment as we discuss in Sect. 2.2.

2.1 Robustness w.r.t. transmitter channel uncertainty

In MIMO transmission CSIT is an essential ingredient. CSIT for downlink transmission in cellular networks is commonly obtained either from uplink measurements, relying on channel reciprocity [15], or from quantized channel estimates provided by the users over dedicate limited capacity feedback links [16]. Either way, the CSI estimate at the transmitter is prone to imperfections, causing residual multi-user interference when applying spatial multi-user multiplexing schemes. This is especially problematic in high-mobility scenarios, where CSIT imperfections are aggravated by fast temporal channel variations. High-mobility situations are therefore not suited for so-called coherent spatial multi-user multiplexing schemes, which rely on destructive multipath interference to mitigate multi-user interference (e.g., zero-forcing beamforming). Better suited are incoherent spatial multiplexing schemes, such as, space division multiple access (SDMA), which attempt to spatially separate multiple users in the angular (azimuth and elevation) domain, by forming transmit beams that are non (or only weakly) overlapping in the angular domain. Such SDMA schemes are, however, limited to situations in which the number of significant multipath components of each user is small and where users are spatially relatively far apart, to enable angular separation of users at the transmitter.

In [3], we develop robust limited CSI feedback methods and non-coherent beamforming techniques for FD-MIMO multi-user transmission that are suitable for high-mobility situations. These methods enable reliable and spectrally efficient multi-user transmission with modest amount of CSI feedback overhead. The method is based on quantizing the angular directions of the most significant multipath components of each user, in order to form transmit beams that steer the signal energy towards the respective intended user while limiting the interference leakage caused to other users. An example of transmit beams obtained in that way is shown in Fig. 1; in this figure, the fully white circle illustrates the angular position of the intended user, while the black circles/rectangles show the positions of other users. The leakage bounded beamforming method developed in [3] allows to incorporate angular uncertainty in the transmit beam design. The left and right plots of Fig. 1 show the resulting transmit beams without angular uncertainty (left) and with angular uncertainty (right); the amount of angular uncertainty is represented by the black rectangles in the right plot. Clearly, accounting for angular uncertainty allows for more robust and reliable multi-user transmission, since imperfections in the angular position estimation are compensated by the more forgiving transmit beam.

Channel measurement campaigns in the mmWave band have revealed that mmWave transmissions exhibit very limited multipath propagation [17, 18]. The main reason for this behavior is that mmWave transmissions require high-gain directive antennas to compensate for the pathloss, which act as spatial filters and thereby effectively reduce the number of significant multipath components. In many cases, the mmWave channel can be characterized by very few (one or two) dominant multipath components. Due to the small wavelength of millimeter waves, the relative phases of these multipath components vary significantly already for tiny variations of the propagation environment. We have observed these effects also empirically through measurements in indoor scenarios. Figure 2 shows an exemplary result of the correlation of the phase of the measured channel as a function of the displacement of the receiver (position $(\Delta x, \Delta y) = (0, 0)$ is the reference position). The noticeable phase correlation pattern in Fig. 2 can largely be explained by two waves interfering at our receiver. We observe that the phase varies significantly even when moving only a few millimeters. This implies that CSI uncertainty of the relative phases of multipath components are practically unavoidable even in virtually static scenarios. Therefore, the so-called two-wave with diffuse power (TWDP) channel fading model [19] is well-suited to describe the fading behavior of

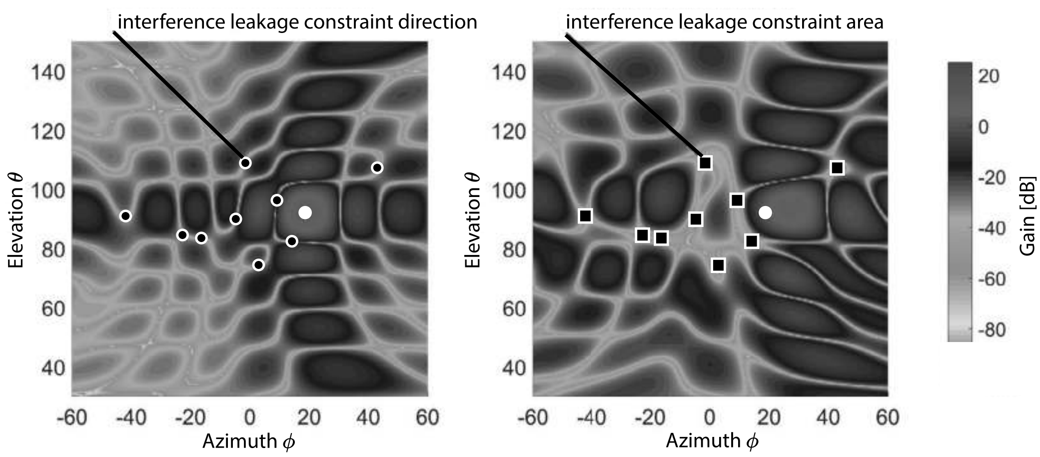

Fig. 1. Radiation beam pattern of leakage bounded beamforming (left) and robust leakage bounded beamforming (right) [3]. The fully white circle corresponds to the angular position of the intended user; the black circles/rectangles represent interference leakage constraints imposed by other users

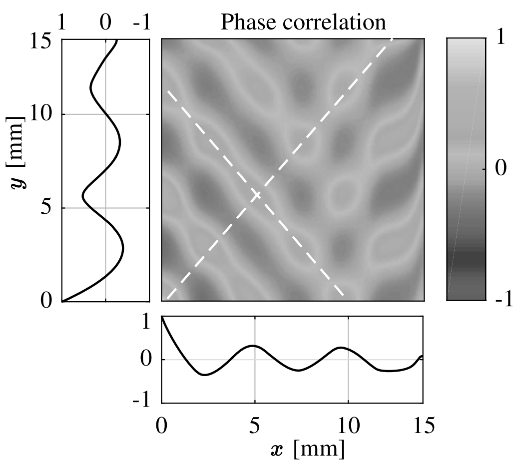

Fig. 2. Correlation of the phase of a mmWave channel measured in an indoor propagation scenario with $(\Delta x, \Delta y) = (0, 0)$ as reference position. The observable pattern is mainly caused by two plane waves interfering at the receiver; their wave fronts are indicated by dashed lines

mmWave transmissions. This is also evidenced by our measurement results reported in [20], where we observe TWDP fading in an indoor mmWave transmission scenario. The TWDP channel distribution can lead to fading behavior that is worse than Rayleigh fading, which significantly impairs the reliability of mmWave links. As we show in [21], smart beamforming at the transmitter, even without knowledge of the relative phases of the multipath components, can reduce the severeness of multipath fading and therefore enhance the reliability. Yet, to achieve high-degree dependable wireless mmWave transmissions, macroscopic diversity in the form of multi-point and/or multi-band connectivity should be provided by the mobile communications system.

2.2 Antenna array geometry and deployment

The most important property related to favorable channel conditions in massive MIMO systems is that channels of different users become asymptotically orthogonal with growing number of transmit antennas. This is, e.g., fulfilled in rich scattering environments (independent Rayleigh fading), but also under line of sight (LOS) conditions provided users can be separated by the transmitter in the angular domain [22]. Favorable channel conditions theoretically allow to serve an unbounded number of users in parallel when the number of transmit antennas grows to infinity. Practically, however, a possibly large but limited number of antenna elements needs to be arranged within a given form factor. Scaling up the number of antenna elements with a fixed form factor does not lead to favorable propagation conditions, since the channels seen by different antenna elements become more and more correlated [23]. This then leads to the important issue of the optimal choice of antenna geometry (i.e., how many antenna elements should be used and how should they be arranged) to achieve the best possible performance. The optimal choice is on the one hand dictated by the achievable spatial resolution of the array, which determines spatial separability of users in the azimuth and elevation domain [24] and therefore affects whether or not such users can reliably be served in parallel, but on the other hand also by impairments of the radio frequency hardware, such as, power losses in phase shifters, phase quantization, etc. [25]. In our research lab, we attempt to address these issues by means of virtual antenna array measurements. In a virtual array approach, in the simplest case, a single antenna element is mounted on a mechanical guide system and is connected via a single cable to a single channel transmitter. By sequentially re-positioning this single antenna element in space and transmitting sounding sequences at each position, an arbitrary antenna array geometry can be virtually formed in space. Yet, such virtual arrays can naturally not incorporate mutual antenna coupling effects, which can lead to overestimation of the performance of full arrays (realizing all antenna elements simultaneously) [26]. To compensate for this effect, we have developed a mutual coupling model [27], which, when applied to virtual array measurement data, allows to closely approximate the performance of full arrays without having to physically build them. This enables us to investigate and compare the performance of different array geometries in our future work, in order to identify geometries that enable reliable multi-user spatial multiplexing in practical FD-MIMO systems.

3. Adaptable multicarrier transmission

Multicarrier transmission in the form of orthogonal frequency division multiplexing (OFDM) builds the PHY-basis of LTE [28]. By suit-

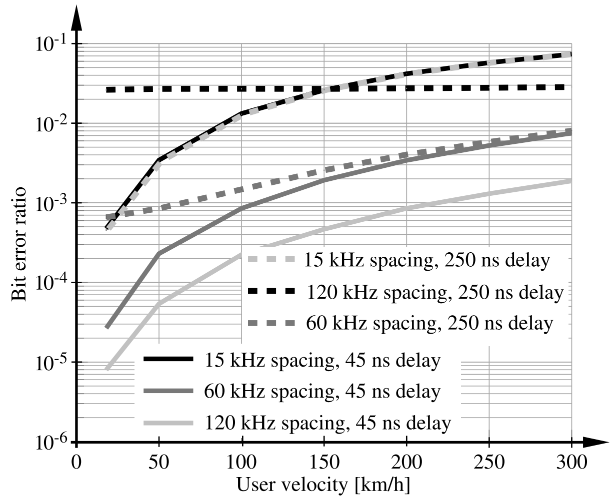

Fig. 3. Bit error ratio of OFDM with different subcarrier spacings as function of the user velocity (determining the channel Doppler-spread) for two different channel delay spreads [30]

able parameter selection, in terms of subcarrier spacing, cyclic prefix (CP) length and symbol duration, also known as the applied numerology of the multicarrier scheme, it is possible to achieve robustness of the transmission w.r.t. channel characteristics (delay- and Doppler-spread) as well as transceiver imperfections (timing and frequency synchronization inaccuracy, phase noise, channel estimation errors). In LTE, a fixed parametrization of the numerology was selected, which appeared suitable during the development phase of LTE for the envisioned operational environments and the quality of the available transceivers.

OFDM-based multicarrier schemes will also be employed in 5G, yet a fixed numerology is not suitable any longer [29]. This is because operating carrier frequencies will vary over a large range (few hundred MHz up to tens of GHz); since transceiver imperfections scale (at best) proportionally with the carrier frequency, it is also necessary to scale the subcarrier spacing correspondingly to avoid performance impairments due to these imperfections. Additionally, 5G BSs and network access nodes are expected to operate in various environments, ranging from large-area coverage in sparsely populated back-country and rural areas, over serving of high-speed vehicular users (cars, trains), to very small-area indoor (single room) hot-spot scenarios. These environments come with grossly distinct channel characteristics in terms of delay- and Doppler-spread, requiring matching parametrization of the numerology to avoid intrinsic interference of the multicarrier scheme. Additionally, the numerology also needs to be adapted w.r.t. requirements imposed by the respective use-case/application. For example, ultra low latency communication calls for very short symbol duration and hence large subcarrier spacing, whereas Internet of Things (IoT) devices that operate in very small bandwidth (e.g. environmental sensors) will be based on small subcarrier spacing to enable cheap and easy implementation. One major challenges in 5G is therefore the optimal selection of the numerology as a function of channel characteristics, carrier frequency and user requirements.

In Fig. 3, we exhibit the performance of different subcarrier spacings as function of the user velocity, which determines the Doppler-spread of the channel, for two different values of the delay-spread (corresponding to indoor and outdoor scenarios). Notice, the bit-error ratio performance in these simulations is determined by intrinsic interference of the multicarrier scheme (inter-carrier and inter-symbol interference); we do not account for other transceiver imperfections here. Furthermore, we have scaled the CP length with the symbol duration; hence, the CP length of 120 kHz subcarrier spacing is a lot shorter than that of 15 kHz. If the delay spread of the channel is shorter than the CP length, which is the case for 45 ns delay spread, larger subcarrier spacings perform better than smaller spacings, since they are more resilient w.r.t. temporal channel variations (inter-carrier interference). However, if the CP length is not sufficient to cover the delay spread of the channel, which happens in case of 250 ns delay spread for 60 kHz and 120 kHz subcarrier spacing, then inter-symbol interference deteriorates the performance. Thus, there exists an optimal numerology for given channel characteristics in terms of achieving the best reliability (alternatively, the optimal numerology can also be selected in terms of maximizing the throughput). In [31], we investigate the optimal reliable numerology of a single user taking additionally imperfect channel estimation into account.

In 5G not only adaptable/flexible numerology will be supported, but even mixing the numerology of different subbands within a transmission band will be allowed [32]. Such mixed numerology implementations are required when different applications/use-cases (e.g. low latency and cheap IoT) and users experiencing varying channel characteristics (e.g. static and mobile users) are served within the same transmission band. Mixing the numerology, however, causes inter-subband interference due to loss of mutual orthogonality of subcarriers. Therefore, enhancements of OFDM are required to reduce the out-of-band emission. Several candidate multicarrier technologies are under discussion within standardizations [33], though a clear vote for one of these technologies is currently not expected; it will likely be a vendor-specific choice that needs to obey certain spectral-mask properties. The best out-of-band emission is achieved by filter-bank multicarrier (FBMC), which is, however, not backwards compatible to LTE and therefore not a suitable technology for application in existing LTE transmission bands.

4. Dynamic network architectures

The static cellular network architecture, which has dominated mobile networks over several decades, is getting more and more outdated with the ever increasing spatial densification of network access nodes. Already within LTE the strict boundaries between different cells have started to disappear due to the introduction of coordinated multipoint transmission (CoMP) and D2D communication. In 5G, cell boundaries will become even less important, since CRAN architectures and further improvements of CoMP technologies will enable large-scale coordination and cooperation of many network nodes. Additionally, public and private transportation vehicles will take the role of network access nodes (relays, small cells) to serve passengers and users in their close vicinity, causing dynamic variations in the network architecture. Below we discuss opportunities provided by these technologies to reduce the outage probability of mobile networks, thereby enhancing reliability.

4.1 Dynamic distributed antenna systems

Network densification runs like a common thread through the success story of cellular networks [34]. This trend of ever increasing spatial reuse of bandwidth will persist within 5G networks, especially since mmWave transmissions are mostly limited to relatively short distance communication. Despite deploying autonomous small cells to densify network architectures, distributed antenna systems (DASs) are another important technology that can enhance

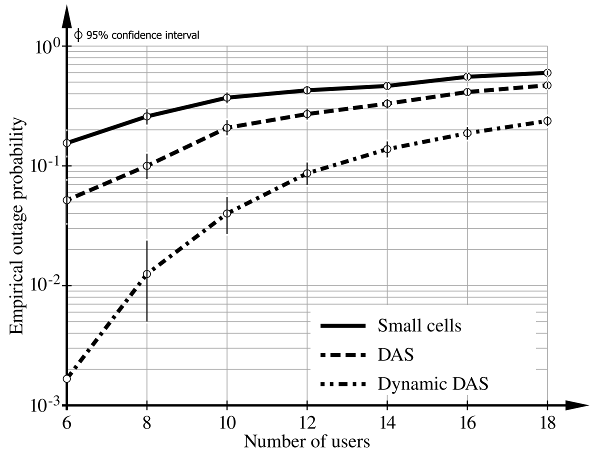

Fig. 4. Empirical outage probability of users served by autonomous small cells, distributed antenna systems and dynamic distributed antenna systems

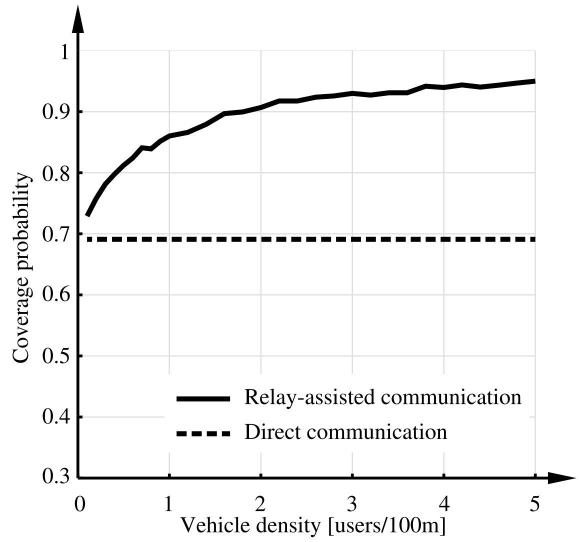

Fig. 5. Comparison of the coverage probability of an urban micro–cellular scenario without vehicle-relays (direct communication) and with vehicle-relays (relay-assisted communication) [38]

network performance by reducing the access distance between transmission/reception points of the network and users. DASs extend the BSs' antenna ports by connecting remote radio heads (RRHs) over dedicated high-bandwidth low-latency connections to the BSs, utilizing e.g. radio-over-fiber technology or mmWave fronthaul [35], thereby enabling spectrally efficient single-user and multi-user MIMO operation by coherent transmission from spatially distributed antenna arrays [36]. Especially the combination of mmWave fronthauling and CRAN is promising, since it enables on-demand formation of DASs by dynamically connecting cloud base band units (BBUs) to RRHs to satisfy user-requirements.

In [37], we investigate a variant of such dDAS, in which existing macro BSs are dynamically connected to RRHs via on-demand fronthaul connections. This approach has the advantage that basic coverage can be provided by the layer of existing macro BSs, whereas the actual high-performance data transmission to the user equipments (UEs) is supported by additional RRHs. The challenge in such systems is to optimize the dynamic allocation of RRHs amongst multiple BSs. In [37] we propose joint RRH allocation and distributed beamforming methods for dDASs with to goal of minimizing the outage probability of UEs. We show an exemplary result of [37] in Fig. 4, where we compare the outage performance of autonomous small cells to DASs with fixed allocation of RRHs amongst BSs (allocation to closest BS) and to the proposed dDAS architecture. Clearly, dDAS can provide a significant improvement in terms of user outage probability, because the dynamic user-centric coordination of RRHs provides a gain in macroscopic diversity. Notice that in combination with mmWave fronthauling such a dDAS architecture can be realized relatively cheaply, since no wired fronthaul is required.

4.2 Vehicles as moving relays

Since release 14 of LTE, vehicular communications is considered as an integral part of mobile cellular networks [39]. Vehicular communications is an important enabler for enhancing the safety on roads by supporting mutual awareness of vehicles, as well as, for improving the efficiency of transportation through intelligent transport systems. Yet, vehicles featuring radio access equipment can also be useful for enhancing the performance of the mobile network itself; specifically, utilizing vehicles as relaying nodes between BSs and conventional UEs (e.g. smart-phones) has significant potential for coverage extension of mobile networks, especially in urban areas where vehicles are basically omnipresent [38]. Thus, equipping vehicles with mobile network access equipment could be a relatively cheap enabler for network densification without requiring dedicated on-premise infrastructure. Vehicular relaying can also reduce the energy consumption of conventional UEs by decreasing the transmission distance, thereby potentially even enabling outdoor mmWave transmissions.

In [38], we investigate the coverage improvement of vehicle-relay-enhanced micro-cellular networks in urban environments. We show an exemplary result of [38] in Fig. 5, which exhibits the reduction of signal outages as a function of the average density of vehicles on the road. We observe that the coverage of the network improves with increasing density of vehicle-relays, due to increased macroscopic diversity. Notice that in the relay-assisted communication scenario relaying is only activated if it is beneficial in terms of coverage; that is, if the BS-to-relay or the relay-to-UE link has worse performance than the direct BS-to-UE link, relaying is not used. In our investigation we only consider relaying by a single vehicle-relay; the performance can potentially be further improved by enabling multi-relay connectivity, thereby enhancing the reliability of the wireless connection by making it resilient even w.r.t. microscopic fading.

5. Conclusion

The fifth generation of mobile wireless communications is expected to enhance the mobile broadband experience, to achieve ultra reliable low latency communications and to support massive numbers of IoT devices. These features have the potential to enable entirely new applications for mobile communications, which require dependable wireless connectivity rather than just best effort services. Our research work within the *Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion* aims at optimizing 5G and beyond mobile communications to realize dependable wireless connectivity for ever more challenging applications. In this paper, we have summarized achievements of our research work so far, showing that indeed many of the novel 5G technologies can enhance the efficiency and reliability of wireless transmissions, provided the available adaptability and flexibility of the communications standard is properly utilized through sophisticated transceiver signal processing and optimized coordination/cooperation of network access nodes.

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