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Millimeter Wave Hybrid Photonic Wireless Links – Also for Broadcast?

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***Abstract*—This paper regards photonically enabled millimeter wave links for use in 5G. Following a short review of the trade-off between link directivity, achievable capacity and coverage area, it discusses the use of optical space division multiplexing as suggested in the 2nd phase 5G-PPP project blueSPACE. Finally it relates the latter to the potential use of millimeter waves for broad- and multicast within the framework of 5G.**

I. INTRODUCTION

As the introduction of the fifth generation of mobile services (5G) is set to revolutionize the way people, devices and machines connect, the changes to the underlying networks and technologies are no less drastic. The massive increase in user and data capacity, as well as the decrease in latency require a complete re-thinking of radio access networks (RANs). The latter brings not only the opportunity for further convergence of the fixed and mobile network segments, but has attracted significant interest for the integration of mobile and broadcast networks [1]–[3].

In order to achieve peak data rates of multiple Gb/s and to enable the required area traffic density, the introduction of millimeter wave (mm-wave) frequencies is essential to provide wireless front-haul with sufficient capacity and to supply the peak rates to the end user equipment [4], [5]. Millimeter wave hybrid photonic wireless links seamlessly merge the wired optical and wireless radio network segments and combine the best of both technologies, offering very large capacity and bridging long distances with optical fiber, while retaining the flexibility of wireless communications [5].

The introduction of advanced multiple-input multiple-output (MIMO) signaling is seen as a key element in the deployment of 5G networks, as massive MIMO in the traditional radio frequency (RF) bands below 6 GHz and in the form of beamforming and -steering envisioned for mm-wave frequencies [4], [6]. While both achieve significant gain in the overall system capacity by increasing the number of antenna elements at both ends, i.e., by employing spatial diversity, they differ significantly in the underlying strategy. While for sub 6 GHz systems MIMO processing is performed digitally, for mm-wave systems analog beamforming is considered more promising to generate narrow, focused beams to deliver better signal quality to the targeted user(s) [4], [7].

This paper will first review the trade-off between link directivity, achievable capacity and coverage area, highlighting the difference between highly directive point-to-point links, transmissions supported by beamforming, -steering or -switching and such where mm-waves are employed for distributed access. It will then discuss the use of optical space division multiplexing in the RAN as suggested by the *blueSPACE* project [8] – launched in 2017 within the European Commission's 5G Public Private Partnership programme (5G-PPP) –, where the use of multi-core fibers is envisioned to feed optical beamforming and -steering networks, while further providing both unprecedented levels of capacity as well as allowing parallel transmission on a number of independent channels. Finally, it casts a brief look at the use of optically enabled millimeter-wave communications for use in broad- and multicasting.

II. MILLIMETER-WAVE HYBRID PHOTONIC WIRELESS LINKS

The use of millimeter wave carriers for 5G networks brings with it a set of challenges different from those in the more traditional RF bands below 6 GHz. While in the lower frequency regions the spectrum congestion is a major limiting factor, with rising frequency the difficulty shifts from spectrum availability to the propagation characteristics, namely large propagation loss, reduced penetration through objects and bodies and – especially for the upper half of the mm-wave range – significant impact of atmospheric absorption and precipitation. As a result, the trade-off between coverage area, required transmitter power and achievable capacity is strongly accentuated.

Figure 1 illustrates this trade-off, with Fig. 1(a) giving a comparison of the path loss for the traditional and the mm-wave frequency bands and Fig. 1(b) showing the achievable capacity for a transmission in the mm-wave rage with different bandwiths and powers or antenna gains. As can immediately be seen, the frequencies in the mm-wave range will suffer a 20 dB increased line of sight path loss compared to current systems at LTE frequencies and will additionally have larger losses from obstacles or even precipitation. As result, most

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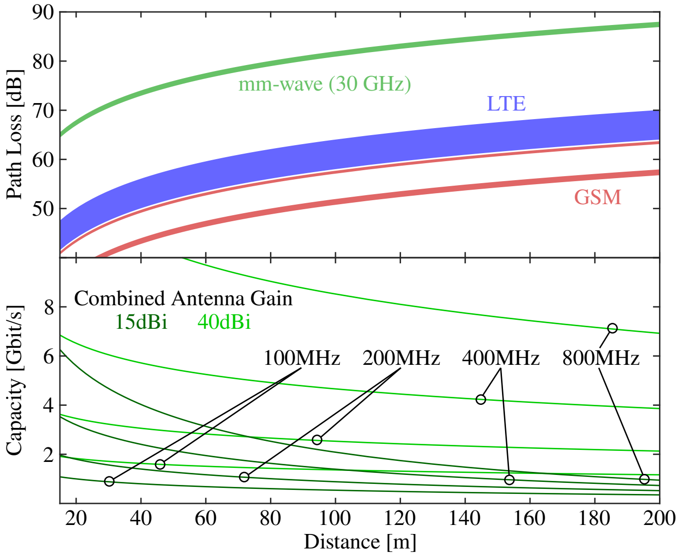

Figure 1. (a) Comparison of path loss between the traditional RF bands and the mm-wave band; (b) Achievable capacity at mm-wave frequencies for different bandwidths and antenna gains.

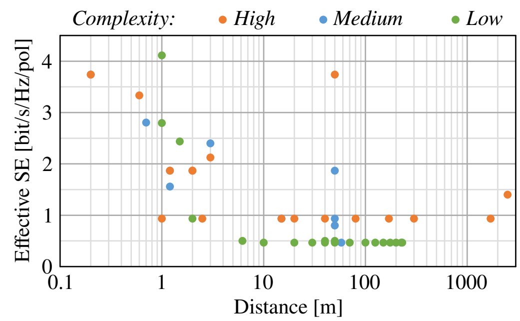

Figure 2. Spectral efficiency over distance for recent experimental demonstrations of point-to-point mm-wave links, classified by their implementation complexity; the points at 50 m and spectral efficiency larger 1.7 bit/s/Hz and 3.5 bit/s/Hz respectively stem from [10] and [12].

mm-wave links either make use of highly directive antennas or beamforming, -shaping and -steering to increase the received power or are severely limited in range, to distances of a few meters.

A. Point-to-Point Millimeter Wave Links

Point-to-point millimeter wave links based on radio-over-fiber transmission have been demonstrated at frequencies covering the whole range of the mm-wave band and beyond. With aggregate antenna gains of multiple tens of dB, they can almost completely offset the path loss for transmission over distances reaching beyond 100 m [9] and thus reach capacities of more than 100 Gbit/s over short ranges or tens of Gbit/s over a few km [10], [11]. Despite reaching such data rates, their spectral efficiency in the RF domain has mainly remained relatively low – even for recent experiments introducing optically generated single sideband modulation [12] – as spectrum availability was regarded as a secondary issue for highly directive and strictly line of sight point-to-point links. Figure 2 shows a comparison of achieved effective spectral efficiency for a number of recent demonstrations, showing the majority to be limited to distances below 5 m or spectral efficiencies around 1 bit/s/Hz.

B. Beamforming, -Steering and -Switching

Similar to the use of highly directive antennas, the use of beamforming can provide increased link performance, while partially mitigating the reduction in coverage by allowing the direction of the beam to be steered [6], [7]. Such flexibility comes at the cost of requiring antenna arrays with tunable differential delays between the feeding signals – typically achieved through electrical phase shifters, true time delays or, more recently, through optical beamforming networks – and with a gain in directivity directly proportional to the dimensions of the array [7].

While typical beamforming networks only allow the generation of a single beam, i.e., consist of a phase shifting network with a single input and as many outputs as antenna elements, techniques for the generation of multiple beams with a single antenna array exist [7], [13].

C. Distributed Millimeter-Wave Access

The use of mm-wave carriers of distributed access has been mainly focused on short range and indoor access in the 60 GHz band, where atmospheric attenuation is large and longer distance transmission is thus infeasible. A series of standards has already been established for indoor and personal area networks in this frequency band.

For use in 5G, initially frequencies around and just below the lower edge of the mm-wave range are targeted, allowing short range distribution and – with beamforming – allowing to provide large capacities to restricted areas or even single users [4]. Fully digital implementations of MIMO in the mm-wave range may be feasible in the future, provided that both a significant decrease in energy consumption for the RF transmitter chain and a significant increase in fronthaul capacity can be achieved.

III. Optical Space Division Multiplexing for 5G Millimeter-Wave Communications

Space division multiplexing (SDM) was introduced in the optical domain to increase the capacity of fiber optics beyond that of standard single mode fibers (SMF) by increasing the number of available spatial channels – through the use of multiple modes or multiple cores or a combination thereof in a single fiber. By increasing the number of spatial channels to above one hundred channels in a single fiber for fibers with multiple cores and modes, the capacity per fiber has scaled similarly. While in optical communications these fibers mainly increase overall capacity, they offer additional and different advantages when employed in combination with heterodyne photonic up-conversion for hybrid photonic millimeter wave links.

In the 2^{nd} phase 5G-PPP project *blueSPACE*, the introduction of multi-core fibers (MCFs) is suggested to meet the capacity requirements envisioned for optical front-haul and to enable

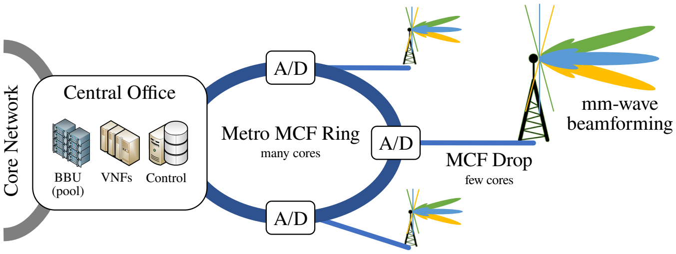

Figure 3. Overview of the *blueSPACE* radio access network architecture, based on analog radio-over-fiber fronthaul, space division multiplexing using multi-core fiber and mm-wave beamforming. BBU: base band unit, VNFs: virtualized network functions, MCF: multi-core fiber, A/D: multi-core add/drop multiplexer.

seamless feeding of advanced optical beamforming networks. The use of MCFs allows further centralization and sharing of RF and processing resources, by providing the capacity to densely deploy small cells. Optical beamforming networks can potentially feed large antenna arrays and provide highly directive and adaptive beamsteering, including the capability to independently generate and steer multiple beams and thus further increasing cell capacity.

blueSPACE targets to implement a centralized radio access network based on MCF as shown in Fig. 3, supporting parallel operation of both digital and analog radio-over-fiber fronthaul and – with the latter – directly integrating optical beamforming networks. To support the various usecases envisioned for 5G and to cope with highly dynamic traffic loads, the project will design a complete control architecture based on the paradigms of software controlled networking (SDN) and network function virtualization (NFV). By combining space division multiplexing in MCF, analog RoF based fronthaul and optical beamforming, the *blueSPACE* concept allows maximum centralization of resources and complex processing functions at the central office as well as enabling more advanced resource allocation and network slicing strategies by increasing the number of available multiplexing domains.

IV. Towards Broad- and Multicast Using Millimeter-Wave Hybrid Photonic Wireless Links

5G millimeter-wave hybrid photonic wireless links may be of interest for broadcasting not only for the final distribution, but also during content generation and production where extremely large capacities are required in an almost point-to-point fashion – potentially involving mobility at one end. The following will briefly introduce a number of potential ways in which mm-wave links can be adapted to and employed for application in broad- and multicasting.

A. Point-to-Point Millimeter-Wave Links in Content Production and Distribution

Point-to-point mm-wave hybrid photonic wireless links offer low latency and immense capacity with constant performance and bit rate, making them interesting candidates for the transmission of high-definition video material during content generation and production [14]. For applications for such nature, traditional point-to-point links with highly directive antennas may be suitable or – if mobility is required – implementations with beamforming and -steering, which allow tracking of a user, may be used.

If a small number of distinct users are generating content at very high data rates, e.g., dedicated ultra high definition video equipment during sports events, connectivity to a centralized, fiber connected point may be provided by multi-beam implementations providing different beams to the users in different locations.

B. Broad- and Multicast Distribution

With the strong trade-off between achievable distance and link directivity and capacity, the use of millimeter waves for broad- and multicast distribution faces challenges beyond those of typical unicast 5G communications. However with the capacities and potential flexibility of beamsteering enabled millimeter wave links, broad- and multicast distribution can be accommodated if they are regarded in combination with unicast transmission and provided efficient and intelligent sharing of resources can be achieved across communication types. While broad- and multicasting within 5G are still under standardization, the use of photonically enabled mm-wave wireless links has been discussed and a few scenarios shall be reviewed in the following.

In a first scenario, the use of mm-wave frequencies for short-range indoor applications, where path loss is at an acceptable level, allows for ultra high definition content distribution within homes, offices or at small venues. Based on the fact that for such distribution antenna gains are necessarily low, this requires ready availability of fiber connectivity at multiple locations to ensure a line of sight path to the user can be established at all times – provided such a link can be established however, it readily provides multi-Gbit/s connectivity with ultra-low latency.

If larger distances must be covered, mm-wave links with beamsteering may be used to broadcast to users located closely to each other and potentially moving at the same speed – such as for providing live onboard entertainment to a train or bus. In such a scenario the required coverage area is small enough to be covered with a single or very few beams, while covering a significant number of users and with beam steering required only at the speed of the moving vehicle [15]. Alternatively, ultra fast beamsteering or -switching can allow sharing of resources between unicast and multicast through time division multiplexing or allow broadcast through scanning of the broadcast area [16]. The use of novel antenna concepts such as phased-array fed reflector antennas [17], [18] may allow both a reduction in the complexity required for beamforming and -steering and an increase in the number of beams. With such simplified feeding structures potentially allowing re-use of a single input signal over multiple beams, a time division based sharing between broad-/multicast with multiple beams carrying the same information and unicast with all beams carrying distinct data may become feasible.

More advanced solutions might further allow the overlay of broad-, multi-and unicast communications through non-orthogonal multiplexing/multiple access (NOMA), allowing for larger area broad-and multicast coverage, while supplying unicast traffic over the same resources [19]–[21]. If combined with time division multiplexing, such solutions may use NOMA to provide user data to users with high signal to noise ratio during time slots allocated for broadcast, without affecting broadcast quality – and thus allow effectively increasing network utilization.

It is common to all the discussed methods and strategies, that they either are very limited in their application or require and additional trade-off to be made between the achievable unicast and broadcast capacities as well as the added system complexity. It is clear that a range of possibilities exist to minimize the impact of allocating resources – be they in the frequency, time or the power domain – for broadcast, by allowing intelligent sharing of resources and optimizing resource allocation ad-hoc, depending on both demand and the specific channel conditions. As both may be highly dynamic, improved resource allocation algorithms, aware of the different natures of broad-/multicast and unicast traffic are required, along with added flexibility and reconfigurability in the network.

V. Conclusions

This paper reviews millimeter wave photonic wireless links for 5G networks, discussing the inherent trade-off between link directivity, achievable capacity and coverage area and its impact on link design, making links with high directivity – through high gain antennas or beamforming – the preferred choice. To support the massive capacities required for fronthaul to densely deployed small cells and to seamlessly feed optical beamforming networks, the use of optical space division multiplexing with multi-core fibers is discussed as envisioned by the 2$^{\text{nd}}$ phase 5G-PPP project *blueSPACE*. Finally, a brief review of usage options for mm-wave frequencies in broad- and multicast applications is given and a number of strategies for resource sharing between broad-/multicast and unicast communications are introduced.

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