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Energy Efficient Line-of-Sight Millimeter Wave Small Cell Backhaul: 60, 70, 80 or 140 GHz?

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Abstract—Spectrum scarcity together with high capacity demands make the use of millimeter wave (mmWave) frequencies an interesting alternative for next generation, i.e., fifth generation (5G), networks. Although mmWave is expected to play a key role for both access network and backhaul (BH), its initial use in the BH network seems more straight-forward. This stems from the fact that, in the BH case, its deployment is less challenging due to the fixed locations of BH transceivers. Still, provided that mmWave spectrum consists of several subbands, each one with different characteristics and thus different deployment constraints (e.g., channel bandwidth, maximum transmission power), a comparison is required in order to gain a better insight into the potentials of each solution. To that end, in this paper, the main mmWave candidate frequency bands are compared in terms of range, throughput and energy consumption. In our results, the bandwidth availability, the maximum transmission power as well as the antenna gains of each BH technology are taken into account, as defined by the Federal Communications Commission. The results are also compared with current industry-oriented state-of-the-art transceiver characteristics in order to gain further insights into the maximum achievable gains of each subband.

Index Terms—Energy efficiency, green communications, LTE-Advanced, mmWave communication, small cell backhaul, 5G.

I. INTRODUCTION

Next generation, i.e., fifth generation (5G), cellular networks are expected to fulfill the capacity requirements of the near future. According to Cisco, the average mobile connection speed will increase 3.2-fold by 2020, i.e., from 2.0 Mbps in 2015 to 6.5 Mbps by 2020. Moreover, global mobile IP traffic will reach an annual run rate of 367 exabytes by 2020, up from 44 exabytes in 2015 [1]. It has been also reported that mobile offload through Wi-Fi or femtocells exceeded cellular traffic for the first time in 2015 [1]. In total, 3.9 exabytes of mobile data traffic were offloaded onto the fixed network each month. One of the key technologies to meet this increase in the bandwidth demands is to use a larger spectrum bandwidth. As the available microwave (μ wave) spectrum is limited, new frequency bands in the millimeter wave (mmWave) spectrum have been proposed to meet 5G requirements [2].

From the architectural point of view, a clear trend is to move towards heterogeneous networks (HetNets), where small

cells (SCs) are deployed in the coverage area of macrocells so as to increase the capacity by offloading the traffic from the eNodeB (eNB) [2]–[5]. As a consequence, the access network (AN) will most likely consist of: i) long-/medium- range eNBs that operate in the sub-3 GHz band (μ Wave) and ii) SCs that use higher frequency bands (e.g., mmWave). Regarding the backhaul (BH) network, i.e., the connection of these base stations to the core network, it seems to be economically prohibitive to have a broadband fiber connection to every SC if the network is very dense. However, a very dense network is desired in order to provide the capacity increase that is required. Consequently, we need to consider a wireless multi-hop architecture that connects the SCs wirelessly to the eNB site, which typically has already a fiber connection towards the core network [3]. As the BH network in this case may become the bottleneck, the use of higher frequencies where large portion of bandwidth is available (e.g., mmWave) seems to be an appropriate solution. In such multi-hop BH topologies, due to the large number of BH links and SCs, the BH network dimensioning becomes more complicated and the energy consumption of the whole network becomes another crucial factor to be considered by an operator.

The mmWave band from 30 to 300 GHz offers a large amount of free spectrum (i.e., around 100 GHz). However, it is discretely distributed in the overall mmWave band with distinct and very specific channel characteristics. For instance, the 60 GHz band (V-band) suffers from severe oxygen absorption in addition to free space path loss. On the other hand, atmospheric absorption above 70 GHz (E-band) drops significantly to less than 1 dB/km and rises again after 100 GHz due to molecular effects [6]. As a consequence, the E-band has low atmospheric attenuation, making it a suitable candidate for long-range wireless transmissions of around 20 km [6]. However, the signal cannot penetrate solid materials very well. Moreover, although the increase in omnidirectional free space path loss with higher frequencies due to Friis Law [7] can be compensated by appropriate beamforming (i.e., higher antenna gain), shadowing actually constitutes a bigger concern for

mmWave signals resulting in outages, rapidly varying channel conditions and intermittent connectivity [8].

To that end, the goal of this paper is to assess the viability of using different mmWave frequencies for SC backhauling in 5G networks. Thus, the main mmWave candidate frequency bands are compared, while taking into account their bandwidth availability, maximum transmission power and antenna gains, as defined by the Federal Communications Commission (FCC). We also compare the theoretically possible values with practical numbers, which are derived from current state-of-the-art transceiver design. The employed propagation model also considers the joint effect of atmospheric and rain attenuation at those frequencies. A power model, which considers both the static and the load-dependent power consumption [9], is also used to assess the performance of the mmWave BH subbands (57-64, 64-71, 71-76, 81-86, and 110-170 GHz) in terms of BH link length and network power consumption. Due to the aforementioned problems that may arise at these frequencies due to obstacles, for a fair comparison we focus only on line-of-sight (LOS) BH link scenarios.

The remainder of the paper is organized as follows. We first give an overview on related work in Section II. An introduction in LOS mmWave BH solutions is provided in Section III. In Section IV, the power consumption model for a BH link is presented together with the path loss model used in this work. In Section V, the settings of the extensive evaluation are detailed together with the results. Finally, Section VI concludes the paper.

II. RELATED WORK

In this section, we briefly review the related work in the area of LOS SC backhauling for 5G networks. In a recent survey [10], an insight on the characteristics of mmWave communications, existing solutions and standards is provided, and potential applications of the mmWave communications in 5G networks are discussed. Due to the huge propagation loss at these high frequencies, beamforming needs to be adopted and highly directional antennas should be used. Thus, on the MAC layer, coordination mechanisms need to be designed and simultaneous transmissions according to spatial reuse schemes need to be scheduled so as to improve network capacity. The authors also explore the applications of mmWave communications, which include the AN and the BH.

Some authors have tried to exploit the benefits that the mmWave offers in the AN. In [4], the throughput of a point-to-point wireless access link is evaluated, while considering systems operating in the V-band (60 GHz), the E-band (70-80 GHz), and both V-band and E-band simultaneously. By also taking into account the impact of channel attenuation, human shadowing, and interference from neighboring devices on the throughput of the link, it is shown that the overall performance of a wireless network can be further improved if the transceivers used in the hybrid HetNet can simultaneously transmit information over both the V-band and E-band spectra. A HetNet composed of eNBs operating at 2 GHz and SCs operating at 28 GHz is considered in [5]; a

3GPP-LTE-compliant time-division duplexing (TDD) frame structure is also proposed, which is capable of supporting a multi-hop transmission via a wireless BH network. The authors evaluate the performance of the mmWave AN in terms of aggregated cell throughput of the SCs. The authors also suggest that a proper distance is maintained among SCs so that excessive interference is avoided. As the placement of SCs may significantly affect the HetNet performance, different case studies are considered; in the best case, an aggregated cell throughput of nearly 13 Gbps can be achieved. The downlink (DL) and uplink (UL) budget analysis for 60 GHz in LOS conditions is provided in [2] focusing on the AN part. A maximum transmission range of 75 m is shown in the DL, with an achievable data rate of 165 Mbps, whereas 25 m can be reached in the UL. The mmWave SC should embed a directive antenna array with electronic beamsteering in order to track the users. This is a big challenge for future products due to the high complexity at the antenna side. In [11], the authors explore the use of several mmWave bands (i.e., 28, 38, 57-64, 71-76, 81-86 and 92-95 GHz bands) for the 5G enhanced local area access. By jointly taking advantage of the huge mmWave bandwidth availability and large antenna arrays, their system achieves peak data rates in excess of 10 Gbps and edge data rates higher than 100 Mbps. In [12], a quality of service (QoS)-aware multimedia scheduling scheme is proposed and tested over a practical scenario where both V band and E band access are available. The provided results show that the higher the carrier frequency the better the performance.

On the other hand, few works focus on the performance of the BH network at different frequencies. The same authors in [2] compare the V-band and the E-band as possible candidates for BH links. They present the link budget for 60 GHz and show that a maximum distance of 100-300 m can be reached, depending on the modulation scheme and emitted power limitations. They also envision that, if not currently available, beamsteering or beamswitching over a large angular sector will enable point-to-multipoint wireless link, making the network self-configuring. An in-band BH approach is investigated in [13] as an attractive solution for both the BH and the AN links. The authors consider a mmWave beamformed system at 28 GHz with uniform linear antenna arrays at both the SC and user equipment sides. In addition, a time division multiplexing (TDM)-based scheduling scheme for in-band backhauling is proposed. The feasibility of the proposed approach is tested in both LOS and non-LOS scenarios. In [14], the energy impact of different BH solutions is studied in future outdoor HetNets under different traffic distributions and BH technologies (i.e., 3, 28 and 60 GHz). The authors show that the BH constitutes a significant part of the total power consumption and that mmWave seems the best choice due to its very high bandwidth. However, a deeper insight on which is the best mmWave solution for the BH in 5G HetNets is still needed. Provided that each frequency band in the mmWave spectrum may have different characteristics and consequently different deployment issues (i.e., channel bandwidth, maximum transmission power according to standardization and/or technology achievements,

power consumption, etc.), a comparison is required in order to provide the research community with a clear insight into which solution can provide the best performance in terms of throughput and energy efficiency.

III. WIRELESS LINE OF SIGHT (LOS) MILLIMETER WAVE (MMWAVE) BACKHAUL SOLUTIONS

The mmWave band, which ranges from 30 to 300 GHz, can be divided into smaller subbands, each one presenting different and very distinct characteristics, also summarized in Table I. Common to those license free or lightly licensed frequency bands is the large portion of available spectrum. In comparison, spectrum and frequency channels at sub-6 GHz (typically 10 MHz to 40 MHz) and 6-42 GHz (ranging from 3.5 MHz to 56 MHz) are either heavily congested or heavily regulated, or both [15]. This is why mmWave technologies have a distinct advantage in terms of spectrum cost and availability. In particular, in this work, the following main subbands are of interest.

A. V band (57-64 and 64-71 GHz)

In general, mmWave technologies are impacted by atmospheric attenuation to a greater degree than lower frequency technologies. Specifically, V band suffers from severe oxygen (or dry air) absorption, which contributes about 15 dB/km of attenuation in addition to free space losses. Transmission at 60 GHz frequencies carries a low risk of interference as it relies on highly directive narrow beamwidth antennas at each end of a link, with no penetration through or reflection from obstacles such as buildings and vegetation [15], [16]. Regulatory provisions of 60 GHz band for various countries in terms of available license-exempt bandwidth, maximum equivalent isotropically radiated power (EIRP) limit and maximum transmit power are summarized in [17]. In particular, the maximum EIRP is equal to [16]

$$EIRP_{max(dBm)} = 85_{(dBm)} - 2 \cdot x_{(dB)}, \quad (1)$$

where x represents the number of dB that the antenna gain of the transmitter (G_{Tx}) is lower than 51 dBi, i.e., $x=51-G_{Tx}$. Depending on the national rules, the 60 GHz band has between 4-9 GHz contiguous bandwidth that is license-free (subject to the corresponding EIRP and transmit power regulations), as shown in Table I.

B. E band (71-76 and 81-86 GHz)

Different from the V-band, atmospheric absorption above 70 GHz (E-band) drops significantly to less than 1 dB/km [6]. In general, E-band has low atmospheric attenuation, mainly caused by water molecules in the air (or water vapour). In general, 70/80 GHz is more likely to be affected by heavy or excessive rainfall, which typically equates to a link distance of a few kilometers depending on the rain region and desired link availability factor [6]. Transmission at 70/80 GHz frequencies, similar to the V band, carries a low risk of interference as it also relies on highly directive narrow beamwidth antennas at each end of a link [15], [16]. In the

70/80 GHz spectrum, two contiguous bands, 71-76 GHz and 81-86 GHz, are regulated with a *light licensing* approach although specific details depend on local regulation rules [18]. Licensing of the 70/80 GHz band in the US is carried out using a two-tier approach to grant a point-to-point link utilizing these bands [15]. The available spectrum blocks mentioned above are generous amounts that can accommodate very dense network deployments. Finally, the maximum EIRP is [19], [20]

$$EIRP_{max(dBm)} = 85_{(dBm)} - 2 \cdot y_{(dB)}, \quad (2)$$

where y represents the number of dB that the antenna gain of the transmitter (G_{Tx}) is lower than 50 dBi, i.e., $y=50-G_{Tx}$.

C. D band (110-170 GHz)

D band presents relatively high atmospheric attenuation due to molecular effects. In addition, it is worth noting that the channel sizes and operating bandwidth of radio frequency (RF) components and systems are generally in proportion to the carrier frequency at which they operate [15]. Hence, at higher frequencies, i.e., D band, there are more Hertz of bandwidth available in proportion to the carrier, as shown in Table I. Moreover, although the omnidirectional free space path loss is much higher for higher frequencies due to Friis' Law [7], it can be compensated by appropriate beamforming (i.e., higher antenna gain) [8].

IV. POWER CONSUMPTION AND PATH LOSS MODEL

In this section, we review the power consumption and path loss models proposed in the literature, which are the base for our numerical evaluation in the next section. The total power consumption of a BH link transceiver operating at frequency f_{BH} can be calculated as [9]

$$P_{total} = N_{TRX}(P_{static} + P_{Tx}), \quad (3)$$

where N_{TRX} is the number of transceiver chains, P_{static} is the static power consumption part, and P_{Tx} the variable part that scales with the load of the transmitted data. The first part accounts for the power consumption of a BH transceiver even when no traffic is transmitted, whereas the second for the transmit power consumption, which may be given by

$$P_{Tx(dBm)} = SNR_{(dB)} + N_{th(dBm)} + NF_{(dB)} + PL_{(dB)} + T_{x_{loss}(dB)} + R_{x_{loss}(dB)} - G_{Tx(dBi)} - G_{Rx(dBi)} + L_{margin}, \quad (4)$$

where SNR is the signal-to-noise ratio, N_{th} stands for the thermal noise, NF for the noise figure and PL for the total path loss. The parameters $T_{x_{loss}}$ and $R_{x_{loss}}$ represent the transmitter and receiver losses, respectively, while G_{Tx} and G_{Rx} are the transmitter/receiver antenna gains and L_{margin} is the link margin. The thermal noise is given by

$$N_{th} = 10 \log_{10}(k_B T(K) B_{(Hz)}), \quad (5)$$

where k_B is Boltzmann's constant in joules per kelvin, T is the absolute temperature in kelvin and B is the channel bandwidth. Then, the total path loss can be expressed as the sum of the

TABLE I
COMPARISON OF MILLIMETER WAVE BANDS FOR SMALL CELL BACKHAULING

	V band	E band		D band
Regulation	Unlicensed	Light licensed	Light licensed	Light licensed
Frequency band (GHz)	57-64, 64-71	71-76	81-86	110-170
Available bandwidth (GHz) (B_{BH})	2x7 [16] (min 500 MHz) [18]	2 x 5 [15], [18]		60 [24]
Antenna gain (dBi) (G_{Tx} , G_{Rx})	37 (max) [18]	43 (min) [20]		Not specified
f_{BH} (GHz) (used in Section V)	60	73	83	140
Rain attenuation parameters for each f_{BH} [23]	$k_H \simeq 0.8606$ $k_V \simeq 0.8515$ $\alpha_H \simeq 0.7656$ $\alpha_V \simeq 0.7486$	$k_H \simeq 1.0764$ $k_V \simeq 1.0711$ $\alpha_H \simeq 0.7268$ $\alpha_V \simeq 0.7150$	$k_H \simeq 1.2063$ $k_V \simeq 1.2034$ $\alpha_H \simeq 0.7058$ $\alpha_V \simeq 0.6973$	$k_H \simeq 1.5504$ $k_V \simeq 1.5568$ $\alpha_H \simeq 0.6543$ $\alpha_V \simeq 0.6514$

free space path loss (PL_{free}) and the signal attenuation due to oxygen, vapour and rain at distance d , as shown in

$$PL_{(dB)} = PL_{free(dB)} + PL_{d(dB)}. \quad (6)$$

The free space path loss is given by [21]

$$PL_{free(dB)} = 20\log_{10}(f_{BH(MHz)}) + 32.45 + 20\log_{10}(d_{(km)}). \quad (7)$$

Then, the attenuation at distance d can be expressed as

$$PL_{d(dB)} = d_{(km)}(L_{vap} + L_{O_2} + L_R)_{(dB/km)}. \quad (8)$$

where L_{vap} , L_{O_2} and L_R corresponds to signal attenuation due to vapour water, oxygen [22], and rain [23], respectively.

The rain attenuation λ_R (dB/km) is obtained from the rain rate R (mm/h) using the power-law relationship [23]

$$\lambda_R = kR^\alpha. \quad (9)$$

Please note that the rain rate depends on the geographical region and the degree to which the link may become unavailable due to rain attenuation. Therefore, it should be selected based on desired link robustness (i.e., for very high link availability need, the worst case scenario should be considered). The parameters k and α are given by [23]

$$k = \frac{1}{2} \left(k_H + k_V + (k_H - k_V) \cos^2 \theta \cos(2\tau) \right), \quad (10)$$

$$\alpha = \frac{1}{2k} \left(k_H \alpha_H + k_V \alpha_V + (k_H \alpha_H - k_V \alpha_V) \cos^2 \theta \cos(2\tau) \right), \quad (11)$$

where θ is the path elevation angle that accounts for the increased path length due to Tx and Rx being at different altitudes and τ is the polarization tilt angle relative to the horizontal ($\tau = 45^\circ$ for circular polarization). The values for the coefficients k_V , k_H , α_V and α_H are determined as functions of frequency, f_{BH} (GHz) (Table 5, [23]) and are given in Table I for both horizontal and vertical polarization of the frequencies under study.

Finally, the maximum transmit power of a transceiver operating at frequency f_{BH} may be given by

$$P_{Tmax(dBm)} = EIRP_{max(dBm)} + T_{xloss(dB)} - G_{Tx(dBi)}, \quad (12)$$

with $EIRP_{max}$ denoting the maximum equivalent isotropically radiated power (given by (1) and (2) for 60 and 70, 80 GHz, respectively).

Fig. 1. Simulation layout for *Scenario B*.

V. PERFORMANCE EVALUATION

In this section, the simulation scenarios and case studies considered for our evaluation are described, whereas the main results are presented and analyzed. Extensive simulations have been executed in MATLAB[®], where the main mmWave BH solutions have been compared, i.e., V band, E band and D band. Specifically, the following mmWave LOS BH technologies have been considered [15], [16], [18], [20], [23], [24]:

- $f_{BH1} = 60$ GHz of $B_{BH1} = 3.5$ GHz channel bandwidth and $G_{Tx_{BH1}} = G_{Rx_{BH1}} = 36$ dBi antenna gain;
- $f_{BH2} = 73$ GHz of $B_{BH2} = 2.5$ GHz channel bandwidth and $G_{Tx_{BH2}} = G_{Rx_{BH2}} = 43$ dBi antenna gain;

- $f_{BH3} = 83$ GHz of $B_{BH3} = 2.5$ GHz channel bandwidth and $G_{Tx_{BH3}} = G_{Rx_{BH3}} = 45$ dBi antenna gain;
- $f_{BH4} = 140$ GHz of $B_{BH4} = [2.5, 4, 8]$ GHz. Please notice that several channel bandwidths have been considered for the D band as no specific values and/or limitations have been found in the literature¹. Hence, for a fair comparison with the other technologies, similar bandwidths have been simulated (i.e., $B_{BH4} = [2.5, 4]$ GHz), while the impact of a higher channel bandwidth is also investigated (i.e., $B_{BH4} = 8$ GHz). Equivalently, provided that no specifications have been found in the literature for the antenna gain requirements of the D band, two different values are considered, i.e., $G_{Tx_{BH4}} = G_{Rx_{BH4}} = [43, 58]$ dBi. It is worth mentioning that the former is used for a fair comparison with the other technologies, while the latter takes into account future antenna advances, as higher antenna gains are expected at higher frequencies.

Regarding the frequency planning, we assume that the same channel bandwidth is reused every two BH links, so that potential interference is mitigated. Furthermore, please note that, although our study focuses on the DL, the selected channel bandwidth values of all subbands are low enough compared to their maximum bandwidth availability (see Table I) in order to allow for frequency division duplex (FDD) schemes to be employed for the two directions of transmission on a given BH link. Moreover, for all BH technologies, $T_{x_{loss}} = R_{x_{loss}} = 5$ dB and $L_{margin} = 15$ dB. The noise figure of the BH link receivers is assumed to be equal to 4.5 dB for 60 GHz, 6 dB for 70-80 GHz and 5.8 dB for 140 GHz [25], [26]. The static power consumption, P_{static} , is selected equal to 3.9 W for 60, 70 and 80 GHz and 0.516 W for 140 GHz according to [25], [26]. Finally, for the mapping of the aggregate BH link throughput to a specific SNR target, the single-carrier mapping of [27] was used, where each step corresponds to a specific modulation and coding scheme (MCS).

A. Scenarios

Two different simulation scenarios are considered. In the first one (*Scenario A*), we focus our analysis on a single BH link in order to highlight the performance of each frequency band in terms of maximum capacity and range under the specific transmit power limitations of each technology.

In the second scenario (*Scenario B*), we consider an LTE-A eNB sector of 500 m radius, overlaid with two clusters of SCs, each one consisting of eight SCs, as depicted in Fig 1. The SC clusters are uniformly distributed within the eNB sector, and the SCs of each cluster are uniformly dropped within the cluster area [28]. According to 3GPP specifications [28], the minimum distance between two SCs is 20 m and between the eNB and a SC cluster center is 105 m. Moreover, the minimum distance of a UE from the eNB is 35 m and from a SC is 5 m. In addition, in each cluster, one SC (the one being the closest to the eNB) is considered to be one hop away from the eNB site and thus plays the role of the aggregator of the cluster

traffic, four SCs (the ones being the closest to the aggregator) are considered to be two hops away from the eNB site and the other three SCs to be three hops away, each one connected to the closest two-hop-away SC of the cluster (see Fig. 1).

For *Scenario B*, we also consider N fixed UEs of different guaranteed bit rate (GBR) throughput requirements, while focusing on the DL case. Specifically, we assume that 60% of UEs demand 150 Mbps, 30% 200 Mbps and 10% 300 Mbps [29]. In addition, hotspot traffic is assumed, where 2/3 of the total traffic is generated in a radius $r = 70$ m from each cluster center according to 3GPP specifications [28] and the rest is uniformly distributed in the sector area. Regarding the AN, the channels allocated to the eNB and to the SCs are assumed to be orthogonal, whereas SCs belonging to different clusters reuse the same bands, thus interfering to each other. Furthermore, each UE is associated with the base station (eNB or SC) that provides the highest received signal. In particular, the user association is based on the reference signal received power (RSRP), which measures the average received power over the resource elements that carry cell-specific reference signals within certain frequency bandwidth [30].

The rest of the simulation parameters of *Scenario B* are summarized in Table II, where f_{AN} denotes the frequency band used in the AN for both the eNB and SCs. Moreover, B_{eNB} and B_{SC} stand for the channel bandwidth of an eNB and a SC, respectively. The parameter c_{max} denotes the maximum number of physical resource blocks (PRBs) assigned to each base station type, whereas P_{max} to the maximum output power (of each base station type). The path loss of a UE from the eNB is represented by PL_{eNB} , whereas from the SC as PL_{SC} ; h_{eNB} and h_{SC} stand for the base station antenna height of the eNB and SCs, respectively. Furthermore, h_m denotes the mobile antenna height, while C_H represents the antenna height correction factor and d the distance between the base station and the UE. Moreover, N_{ant} stands for the number of antennas. The slow fading is modeled by a log-normal random variable with zero mean and deviation 8 or 10 dB in the case the signal is transmitted by an eNB or a SC, respectively.

B. Case studies

For each scenario, two different case studies are considered for the BH technologies. In the first one (*ideal case*), which can be also considered as the theoretically possible case, the parameters specified in Table I are used based on standardized numbers. The maximum transmit power is equal to 24 dBm for 60 GHz as derived from (1), 33 dBm for 70 GHz, and 35 dBm for 80 GHz, as derived from (2). Provided that no maximum output power is specified for 140 GHz, we use (2) for a fair comparison; as a result, the maximum transmit power is equal to 33 dBm for 43 dBi antenna gain and 32 dBm for 58 dBi antenna gain.

On the other hand, in the *state-of-the-art* and more realistic case, parameters stemming from current state-of-the-art mmWave transceiver designs are taken into account. To that end, according to [25], [26], the maximum transmit power is

¹The experiment in [24] refers to indoor scenarios.

TABLE II
SIMULATION VALUES OF SCENARIO B

Parameter	Value	Parameter	Value
f_{AN} (eNB and SCs)	2.0 GHz	h_{eNB}	25 m
B_{eNB}, B_{SC}	2x20 MHz	h_{SC}	2.5 m
c_{eNBmax}, c_{SCmax}	200	h_m	1.5 m
P_{eNBmax}	46 dBm	$G_{T_{eNB}}$	17 dBi
P_{SCmax}	30 dBm	$G_{T_{SC}}$	5 dBi
PL_{eNB}	$69.55+26.16 \log f_{AN}-13.82 \log h_{eNB}-C_H+(44.9-6.55 \log h_{eNB}) \log d, d$ in km	$G_{R_{eNB}}$	0 dBi
PL_{SC}	$69.55+26.16 \log f_{AN}-13.82 \log h_{SC}+(44.9-6.55 \log h_{SC}) \log d, d$ in km	N_{FUE}	9 dB
C_H	$0.8+(1.1 \log f_{AN}-0.7) h_m-1.56 \log f_{AN}$	N_{th}	-174 dBm/Hz
$N_{ant_{eNB}}, N_{ant_{SC}}$	8

Fig. 2. Atmospheric attenuation (i.e., due to vapour water and oxygen) versus BH link length for different BH technologies, with total air pressure $P_h=1013.25$ hPa, temperature $T=25^\circ\text{C}$ and water vapour concentration $\rho_0=7.5$ g/m³.

Fig. 3. Rain attenuation versus BH link length for different BH technologies and rain rates R , with 0° path elevation angle and horizontal polarization.

23.5 dBm for 60-80 GHz, and 9.2 dBm for 140 GHz. The gap between the *ideal case* and the practical *state-of-the-art case* illustrates the theoretical performance improvements that can be achieved by researching and developing more efficient mmWave transceiver components, e.g., power amplifiers, etc.

C. Results

1) *Scenario A*: In Fig. 2, the atmospheric attenuation versus the BH link length is shown for different BH technologies. As

(a) *Ideal case*

(b) *State-of-the-art case*

Fig. 4. Variable BH link power consumption versus maximum BH link length for different BH technologies in the *ideal case* (a) and *state-of-the-art case* (b). The BH link throughput is set to 1.5 Gbps and $R=50$ mm/h.

it can be observed, 60 GHz presents the highest attenuation due to oxygen absorption at this band, which increases significantly for higher BH link lengths. Still, it is worth noting that for BH link lengths shorter than 200 m, atmospheric attenuation only equals to 3 dB, which makes 60 GHz a good BH solution for short BH links. In addition, 140 GHz presents higher attenuation than the 70 and 80 GHz, since the vapour water attenuation is higher at this frequency band.

In Fig. 3, the rain attenuation is shown versus the BH link

Fig. 5. Maximum achievable throughput versus BH link length for different BH technologies and $R=50$ mm/h (both *ideal* and *state-of-the-art* case).

length for different BH technologies and rain rates R . It can be noticed that higher frequencies present higher rain attenuation, i.e., 140 GHz band presents the highest attenuation compared to the other technologies. Moreover, obviously, the higher the rain rate, the higher the attenuation of the BH technologies under study. However, it is worth noticing that for short BH link lengths up to, e.g., 200 m, rain attenuation is not a limiting factor, since it only accounts to up to 5 dB losses.

Regarding the *ideal* case, the transmit power consumption of a BH link is shown in Fig. 4(a) versus its maximum length for all different BH technologies, when the BH link throughput is equal to 1.5 Gbps. For 140 GHz, several channel bandwidths and antenna gains are considered, as already commented. In general, we refer to each BH solution in the figures as “ f_{BH} (B_{BH} , G_{Tx})”. As it can be observed, 140 GHz with 58 dBi antenna gain presents the best performance, since it is able to offer 1.5 Gbps for a much longer range, i.e., for up to 2.31 km, with the lowest transmit power consumption compared to the other technologies. It is also worth noticing that when higher bandwidth is available, the performance of 140 GHz is improved. Still, the antenna gain affects the maximum range of the D band in a much higher extent than the available bandwidth. This stems from the fact that high gain antennas are able to compensate the experienced path loss. At this point, we should point out that, due to the high frequency and consequently the small wavelength of mmWave frequencies, the antenna aperture can be made much smaller compared to the μ wave band, without compromising gain and directivity, which further favors the use of mmWave for SC backhauling.

Regarding the *state-of-the-art* case, in Fig. 4(b), we show the transmit power consumption of a BH link that is achievable with current transceiver design versus its maximum length for 1.5 Gbps BH link throughput for all BH technologies. Compared to the *ideal* case, the range of all subbands is lower in real implementations. In particular, the maximum range of 60 GHz is 470 m instead of 480 m in the *ideal* case (2% decrease). Equivalently, the maximum range is 0.99 km from 1.35 km for 70 GHz (26% reduction) and 1.08 km

from 1.52 km for 80 GHz (29% reduction). For 140 GHz, the range decrease is up to 66% in the case of 43 dBi and up to 40% for 58 dBi. In general, the higher the frequency the higher the deviation between *ideal* and *state-of-the-art* implementations, since current technology electronics become less efficient at higher frequencies. Moreover, given that in real implementations the maximum transmit power is lower (due to the lower efficiency of the amplifiers), the range decrease is higher for low antenna gains, since in this case higher transmit power is required. Still, the trend is maintained in both *ideal* and *state-of-the-art* cases, with V band being devoted for shorter distances, and D band for longer distances especially if technology allows high antenna gains.

Please note that for higher BH link throughput, and thus higher capacity needs, the maximum BH link range of all BH technologies would further decrease. As an example, if the BH link throughput is increased to 5 Gbps, the maximum range is decreased to 280 m at 60 GHz, 970 m at 70 GHz and 1.13 km at 80 GHz. In addition, for higher BH link throughput, the impact of the available bandwidth would become more important (e.g., in the case of 5 Gbps BH link throughput, the BH link range of the D band with 58 dBi antenna gain increases at a higher rate, from 1.76 km to 2.15 km, when the bandwidth is increased from 2.5 to 8 GHz). Finally, compared to the *state-of-the-art* case, the range decrease would be higher (e.g., 4% at 60 GHz, 33-35% in the E band, 77% and 47% at 140 GHz with 43 dBi and 58 dBi, respectively, in the case of 5 Gbps), since the maximum transmit power would be reached at an earlier point due to the higher BH capacity need.

To gain further insights, we depict in Fig. 5 the maximum achievable throughput of each BH technology (i.e., when the BH transceiver is using its maximum transmit power with current state-of-the-art technology) versus the BH link length. Provided that the maximum transmit power with current technology is lower than in the *ideal* case for all BH technologies, this graph corresponds to both *ideal* and *state-of-the-art* cases. As shown in Fig. 5, the achievable throughput of each BH technology is a step function, with each step corresponding to a different MCS. It is worth noticing that the available bandwidth of each BH technology defines the maximum achievable throughput when a specific MCS is used. As a result, 140 GHz with 8 GHz bandwidth achieves the highest BH capacity (up to 17 Gbps) followed by 140 GHz with 4 GHz bandwidth which allows for up to 8.5 Gbps BH link throughput. The next in terms of BH link capacity performance is 60 GHz with 3.5 GHz bandwidth which allows for up to 7.5 Gbps BH link capacity and then the rest of the BH technologies with 2.5 GHz bandwidth that can achieve up to 5.5 Gbps BH link throughput. Consequently, for short BH link lengths, the higher the available bandwidth, the higher the maximum achievable throughput for all BH technologies.

Nevertheless, as shown in Fig. 5, the BH link range, when a specific MCS is used, depends on the employed antenna gain, i.e., the higher the antenna gain, the higher the BH link range. As a result, 140 GHz with 8 GHz bandwidth and 58 dBi antenna gain presents the highest BH capacity for the

Fig. 6. Average network throughput (a) and average BH network energy efficiency (b) versus number of UEs with $R=50$ mm/h (*ideal case*).

highest BH link range (up to 930 m), thus representing the best solution for long range high capacity BH links. On the contrary, when very high antenna gains are not feasible, 140 GHz with 8 GHz bandwidth and 43 dBi antenna gain can be employed so as to guarantee high BH link throughput; however, shorter BH link lengths are achieved, which, in a practical cellular network, may correspond to a higher number of BH link hops.

2) *Scenario B*: In this scenario, we study the performance of the different BH technologies under study in a LTE-A network as depicted in Fig. 1. To that end, in Fig. 6, the average network throughput (a) and the average BH network energy efficiency (b) are depicted versus the number of UEs for the *ideal case*. Given the specific GBR demands of UEs, the higher the number of UEs, the higher the total network traffic. As it can be observed in Fig. 6(a), 140 GHz with 8 GHz bandwidth achieves the highest network throughput for both considered antenna gain values. This is due to the fact that the very high bandwidth availability is able to offer much higher BH link throughput (of the order of Gbps). As a result, the

Fig. 7. Average network throughput (a) and average BH network energy efficiency (b) versus number of UEs with $R=50$ mm/h (*state-of-the-art case*).

second highest performance in terms of throughput is achieved by 140 GHz with 4 GHz bandwidth. On the other hand, 70 and 80 GHz as well as 140 GHz with 2.5 GHz bandwidth present the lowest throughput due to their lower bandwidth availability compared to the other technologies, which results in the BH network becoming the bottleneck for total traffic higher than 15 Gbps (see Fig. 6(a)). Still, in terms of energy efficiency (see Fig. 6(b)), 140 GHz outperforms the other two subbands (70, 80 GHz), due to the much lower power consumption (the fixed power consumption is much lower for 140 GHz compared to the other subbands²).

Fig. 7(a) and Fig. 7(b) show the average network throughput and the average BH network energy efficiency, respectively, versus the number of UEs using current *state-of-the-art* mmWave transceiver design. Compared to the *ideal case*, the performance of 140 GHz with 43 dBi antenna gain is much lower in the *state-of-the-art case* both in terms of throughput

²Under the assumption of the same fixed power consumption for all mmWave technologies, the performance order of subbands in terms of energy efficiency would be the same as the one in terms of throughput.

and energy efficiency. This is clearly a result of the lower maximum transmit power in real implementations due to low power amplifier efficiency at higher frequencies that cannot be compensated by the antenna gain. By using a higher antenna gain (58 dBi), however, both network throughput and energy efficiency of 140 GHz are increased. Moreover, the lower the available bandwidth, the higher the energy efficiency decrease of 140 GHz (with 43 dBi gain). This stems from the fact that under low bandwidth availability, the maximum transmit power is reached at an earlier point (i.e., for lower traffic).

VI. CONCLUSION

In this paper, we focused on mmWave frequency bands as a promising solution for high capacity BH links for 5G HetNets. As dense SC deployment is expected to provide localized capacity on demand, an efficient BH technology able to serve the increased UE demands is required. As such BH solution should be wireless in order to reduce the costs to roll out fiber to each SC, mmWave band offers an interesting alternative due to the large amount of available spectrum. However, when the SC network becomes very dense, the energy to run such a network is another important factor to be considered. Provided that different subbands present different characteristics in terms of propagation and energy efficiency, a comparison among them in terms of range, throughput and energy consumption was performed in order to gain a clear insight into the potentials of each solution.

Based on an extensive numerical evaluation, 140 GHz was shown to be a very promising solution mainly due to the possibility of highly directive beams (high antenna gains are possible at high frequencies) as well as its high bandwidth availability. The provided results were also compared with real implementations based on current state-of-the-art transceiver design. To that end, a higher deviation between *ideal* and *state-of-the-art* scenarios was observed for higher frequencies (i.e., 140 GHz), since current generation of electronics are less efficient at higher frequencies, thus limiting the maximum transmit power of the BH transceivers. Still, even in *state-of-the-art* scenarios, 140 GHz remains a promising solution, as it achieves high energy efficiency, while at the same time having the highest spectrum availability. However, to fully exploit the potential of such high frequencies, more effective transceiver components such as power amplifiers are required.

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