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Multipath multihop mmWave backhaul in ultra-dense small-cell network

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ABSTRACT

Ultra-Dense Network (UDN) is considered to be the key enabler for realizing capacity goals set by 5G. The major concern in UDN deployment is the backhaul network, which should be scalable, cost-effective, and have sufficient capacity to support massive small cell traffic. Otherwise, the backhaul can become the bottleneck of the network. In this paper, we propose a wireless backhaul solution for UDN deployment by considering MultiPath-MultiHop (MPMH) backhaul architecture in mmWave frequency band. In addition, we propose a distributed routing scheme to forward the backhaul traffic over the multihop network. Backhaul capacity and line-of-sight probability of the proposed backhaul architecture for various picocell densities were compared with direct, multiple-association, and multihop backhaul schemes under interference limited scenarios in outdoor and indoor small cell deployments. The simulation results indicate that the MPMH mmWave backhaul is the most cost-effective and scalable solution for UDN deployment.

1. Introduction

By 2020, a massive increase in network capacity will be required to meet the ever increasing traffic demand. Therefore, fifth generation mobile communication (5G) is envisioned to increase the capacity of existing networks by 1000 fold [1]. In addition to improving the spectral efficiency and using of larger bandwidths, network densification is considered to be a major capacity-enhancing tool to realize 5G data traffic requirements. The basic idea of network densification is to bring the Base Station (BS) closer to users, thus improving the link quality due to shorter distance and enhancing the network capacity as the spectrum is increasingly reused.

The density of the network can be increased by deploying larger number of BSs in a given area or increasing the number of communication links per unit area. Network densification is already used by operators to enhance the network capacity in the form of picocell, femtocell, and Remote Radio Head (RRH) deployments in existing Heterogeneous Networks (HetNet). However, the coverage environment of an Ultra Dense Network (UDN) is very different from the existing HetNet. In UDN deployments, the distances between the Small cell BS (SBS) and User Equipments (UEs) are largely reduced, and a UE is in the coverage area of multiple SBSs as the SBS density is much larger than the UE density. Many of the SBSs are inactive in the case of UDN as they do not have any UE connected. Moreover, the probability of the existance of a Line of Sight(LoS) path between the SBS and UE in UDN is high because of the short distances. However, severe inter-cell interference occurs due to short Inter-Site Distance (ISD).

Small cells in UDN connect with the remaining network through a backhaul connection to Macrocell BS (MBS). The capacity of the backhaul link is considered to be the bottleneck in UDN deployment as it should forward immense small cell traffic into the core network. Wired backhaul is not feasible in the case of UDN because of the large number of small cells and their incremental unplanned deployment. Therefore, several hybrid wired/wireless backhaul solutions have been proposed for UDN deployment. In hybrid backhaul, a section of the backhaul network is connected over wireless links, while the remaining section has wired connectivity with the core network. The wireless schemes employed in these hybrid solutions include self-backhaul [2], multiple-association [3, 4], and millimeter-wave (mmWave) backhaul [5]. In self-backhaul, both access and backhaul links share the same spectrum. The capacity and resource allocation between access and backhaul links are the major concerns in self-backhaul. With multiple association, a user connects with more than one SBS in its area, thus overcoming the backhaul limitation of a single cell. The mmWave backhaul uses frequencies in the range of 30–300 GHz for the backhaul links, thus utilizing the wide spectrum available in this band to realize a throughput of gigabits per second (Gbps). High spatial reuse due to large atmospheric attenuation and the prospects of having compact antennas with narrow beams at

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mmWave frequencies that can mitigate co-channel interference makes mmWave backhaul a promising solution for UDN. However, owing to high path losses at mmWave frequencies, mmWave backhaul only suits short communication range, especially for small cells deployed in the indoor environment.

As small cells in UDN are expected to be deployed incrementally without detailed network planning, some may not find a direct backhaul to the core network, thus requiring an SBS to establish a multihop backhaul link. As a result, the SBS may forward traffic to a nearby small cell to reach a node that can connect it with the core network. User association in UDN environment is further complicated with multihop backhaul as the backhaul aware cell assignment must be considered. In this context, we investigated the MultiPath-MultiHop (MPMH) mmWave backhaul for UDN in this study. A hybrid optical/mmWave solution is proposed in which mmWave backhaul is considered between small cells and the picocell, while the picocell is assumed to have a dedicated fiber optic link to the operator core network. In our proposed scheme, SBS establishes multiple backhaul links to the picocell over the intermediate small cells. We assessed the backhaul performance in terms of throughput, LoS probability, and overall feasibility of various backhaul solutions. We also evaluated the infrastructure requirement of each backhaul scheme in terms of the required number of picocells with wired connectivity to the core network for a given backhaul throughput.

Several studies have analyzed the multihop architecture for mmWave networks. In Ref. [6], performance gain of 60 GHz mmWave Wireless Personal Area Network (WPAN) due to multihop architecture was studied, and the routing and scheduling problem was investigated. Results indicate that compared to single hop, the throughput of multihop network increased by 20%–30% because of shorter links and larger link density. A solution for user association in multihop backhaul scenario for small cell HetNet was proposed in Ref. [7], by considering the energy efficiency and backhaul constraints. The Pareto optimal analytical results derived for the user association problem provide an insight into the trade-off between energy and spectrum efficiency of the network. In Ref. [8], a routing algorithm based on a Multiple Disjoint Spanning Tree (MDST) was proposed for multihop mmWave backhaul in 5G small-cell networks.

The proposed scheme generated multiple disjoint routes between ordinary and gateway nodes that can be used for load balancing and fault recovery, while the ST was spread to balance the traffic between different STs. A joint scheduling and congestion control scheme for mmWave multihop mesh network was studied in Ref. [9]. The results for maximum throughput of multihop mesh network under fairness constraint and dynamic duplex resource allocation mode indicated the improvement in usage of BS physical layer. An MPMH scheduling scheme for mmWave WPAN was proposed in Ref. [10] to enhance the network performance in terms of transmission delay and throughput. The study shows that the MPMH scheduling improves the fairness in distribution of traffic flows over the network.

Most of these studies focused on the applications of mmWave in WPAN and did not analyze the performance specifically in ultra-dense small cell environment. Furthermore, many of the current studies either approximated the mmWave links as pseudo-wires, thus completely ignoring the interference, or considered the K-hop interference model without considering the idle mode capability of SBSs. In this paper, we evaluated the performances of multihop and MPMH mmWave backhaul based on the features specific to UDN. We employed the actual interference experienced by each link based on the activity of the interfering nodes and compared it with other possible mmWave backhaul solutions for UDN, such as direct (single hop) and multiple-association.

This paper is organized as follows. Section 2 presents an overview of various wireless backhaul solutions for UDN. In Section 3, we propose an MPMH wireless backhaul solution for the UDN deployment and propose a distributed routing scheme. Simulation results and performance analysis are presented in Section 4. Finally, conclusions and future research directions are presented in Section 5.

2. Related works

The UDN performance depends on the capability of its backhaul network. Although the UDN capacity requires wired backhaul, it is not practical and economical to deploy a wired backhaul connection at each small cell in UDN. However, wireless backhaul usually has lower throughput and high latency and its capacity depends on the link distance and radio environment. Therefore, wireless backhaul is termed as non-ideal compared to wired backhaul. However, in the case of ultra-dense small cell deployments, wireless backhaul of small cells combined with the wired backhaul of higher network tier, e.g., picocells, could be the only viable solution. The wireless backhaul solutions discussed in literature can be categorized as self-backhaul (in-band) and non-self-backhaul (out-of-band).

Self-backhaul offers a flexible and cost-efficient solution for UDN as the access and backhaul links share the same spectrum and have identical radio access technology. These solutions are also referred to as in-band backhaul as the access and backhaul links are multiplexed on the same frequency band in time or frequency. The capacity and resource allocation between access and backhaul links are major concerns in self-backhaul solutions, and several studies have addressed these issues. A joint user association and resource allocation scheme based on self-backhaul for UDN was proposed in Ref. [11], and optimal bandwidths for access and backhaul links were calculated. The feasibility of in-band backhaul at mmWave frequencies was investigated in Ref. [12]. It was shown that the access link capacity was not significantly affected by the availability of larger bandwidths in mmWave spectrum. To address the backhaul limitation of an individual cell in UDN, Kamel et al. [13] proposed a user association to multiple small cells in the downlink. High aggregate data rates were realized through multiple association as the user distributes traffic among many cells in the vicinity. The performance limit of UDN under limited backhaul capacity was investigated in Ref. [14], assuming cooperation between SBSs to alleviate interference. It was shown that for a limited backhaul, the average per-user rate converged to a fixed value with the increasing number of cooperating BSs. Han and Ansari [15] studied a backhaul-constrained small cell network and proposed a traffic load balancing scheme with hybrid power supply. In Ref. [16], in-band wireless backhaul using massive MIMO systems was studied; it allows high degree of spatial multiplexing. In addition, various duplex techniques for improving throughput over in-band backhaul links were investigated.

Non-self-backhaul solutions for UDN employ different radio access techniques and operate at a different frequency band compared to the access links. The non-self-backhaul solutions avoid the interference between backhaul and access links; however, the interference between picocell and each of its associated small cells still exists. Several studies have analyzed these out-of-band backhaul solutions for UDN using microwave and mmWave frequencies. The availability of a larger bandwidth in the mmWave band and the possibility of designing small antennas with very high gain make mmWave backhaul an attractive solution for UDN deployment. However, link outages due to severe degradation in channel quality by obstacles, weather conditions, and dependence on LoS connection are the major challenges in the designing of an mmWave backhaul solution for UDN. The feasibility of massive MIMO-based mmWave backhaul for UDN was studied in Ref. [17], and a hybrid precoding and channel estimation scheme was proposed that enabled the MBS to simultaneously support multiple SBSs with multiple streams per SBS. A Spanning Tree (ST)-based routing solution for mmWave backhaul was proposed in Ref. [8] to cope with frequent link degradations and failures. Coldrey et al. [18] investigated the viability of microwave backhaul for small cells and the microwave backhaul was shown to be capable of providing high performance gigabit capacity even in Non-LoS (NLoS) conditions.

3. Multipath multihop backhaul

In this study, we focused on a hybrid backhaul solution for UDN,

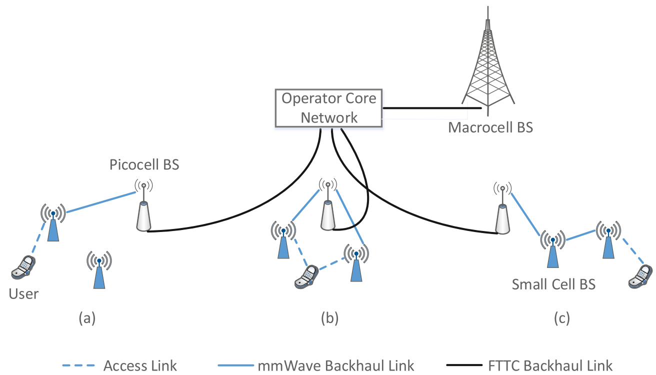
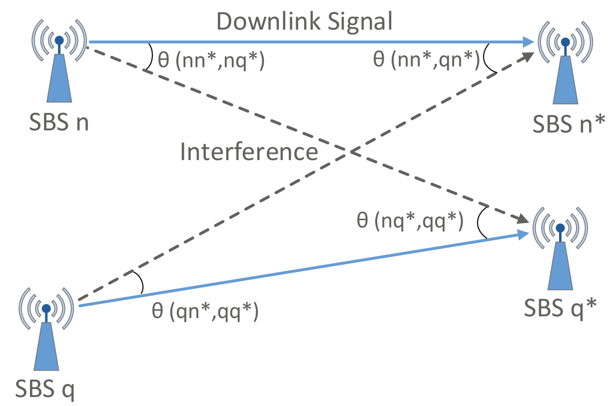


Fig. 1. Backhaul schemes for UDN: a) Direct; b) Multiple-Association; and c) Multihop.

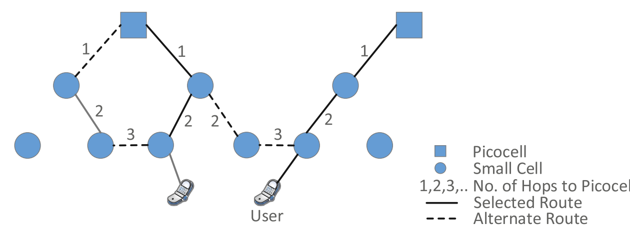
employing mmWave wireless backhaul. mmWave backhaul is one of the most promising solutions for wireless backhaul in UDN as it can provide large bandwidths that can support the high data rate requirement of 5G. However, owing to severe channel attenuation at mmWave frequencies, the quality of mmWave backhaul link deteriorates significantly with the increase in communication range. Therefore, mmWave backhaul requires the picocells with wired backhaul to the core network to be in close proximity to the SBS to have a good backhaul connection. This requires the deployment of a large number of picocells by the operator; this would not be economical. However, the number of picocells with wired backhaul can be reduced if we consider multihop backhaul links between small cells and the picocell. The multihop architecture has certain advantages. By using the multihop architecture to split a long backhaul link into multiple shorter communication links, the achievable data rate over the backhaul link could be further increased because of the improved path loss. Moreover, the shorter links reduce the interference range, thus creating the possibility of the higher reuse of backhaul frequencies. In this context, we propose MPMH mmWave backhaul for UDN, in which SBSs establish multiple backhaul links to the picocell over intermediate small cells. Moreover, owing to directional communication and high penetration losses, mmWave links are highly susceptible to blockage. Blockage refers to very large signal attenuation caused by obstacles, and it cannot be overcome simply by adjusting the transmission power or antenna gain. Simultaneous multihop backhaul connections over different intermediate SBSs in MPMH architecture can significantly reduce the link outages due to blockage. Therefore, the proposed MPMH solution improves the reliability of the mmWave backhaul in addition to improving the overall network throughput.

3.1. MPMH system model

The MPMH backhaul solution proposed for UDN deployment in this study is a special case of multihop backhaul, as shown in Fig. 1c. With MPMH, a small cell distributes the backhaul traffic over more than one intermediate small cell, therefore employing more than one path to relay the backhaul traffic to picocell. To evaluate the throughput performance and wired-picocell density required by the hybrid backhaul network, the performance of the proposed solution was compared with direct, multiple-association, and multihop backhaul schemes shown in Fig. 1a–c, respectively. The backhaul throughput in the case of multiple association was calculated as the aggregate throughput of all the backhaul links for the small cells that a user is associated with, while the throughput of direct backhaul only depends on the link between the small cell and picocell. In the case of multiple association, a UE is assumed to be able to simultaneously connect with a maximum of two small cells. For multihop solution, the backhaul throughput is the throughput of the weakest link over the multihop path. A maximum of two hops were considered for the multihop backhaul. In the case of MPMH, backhaul throughput is the net



(a) Interference between SBSs.



(b) Multihop Backhaul Routing.

Fig. 2. System model.

throughput of all the multihop paths. The MPMH results are presented for a maximum of two multihop paths.

3.2. Deployment scenario

In the UDN considered in this study, the small cell density λ_s was assumed to be much larger than the user density λ_u, implying that many SBSs will be in the idle mode. It is assumed that there is no interference from the SBSs in idle mode as they are completely turned off. The small cell activity was modeled by randomly assigning the users to SBSs, with a maximum of one user per small cell. As small cell density is much larger than the user density, and the user connects with the small cell offering the best service; this indicates that some of the small cells may not have any users associated with them. SBSs are randomly distributed within the coverage area of a macrocell. For backhaul, small cells connect with the nearest picocell and forward their backhaul traffic to the picocell through mmWave communication links. The aggregated backhaul traffic at the picocell from all the connected small cells is relayed to the operators' core network, which consequently connects the small cells with the rest of the network. It is assumed that the picocells have Fiber to the Cell (FTTC) that connects with the core network. We assume that the transmission power of each picocell and small cell are P_p and P_s, respectively, equipped with a single antenna. Electric beam steering was used to connect with neighboring small cells. As sub-bands are typically not considered in mmWave band, all the active small cells in the coverage range of an SBS can be significant interferers and were included in the interference measurements at each SBS. For interference between SBSs, we employed the directional antenna gain model shown in Fig. 2a [19]. The downlink interference at SBS n^* from SBS q is $P_s G_{qn^*} g_{qn^*}^2 \xi(\theta(qn^*,qq^*))\xi(\theta(nn^*,qn^*))$, where G_{qn^*} is the channel gain between SBS q and SBS n^*, and g_{qn^*} is the maximum antenna gain between SBS q and SBS n^*, when their beams are exactly pointing at each other. Here, θ is the offset angle from the peak gain direction and $\xi(\theta)$ is the function of θ in [0, 1], with $\xi(0) = 1$. The downlink signal at SBS n^* from SBS n is $P_s G_{nn^*} g_{nn^*}^2 \xi(0)\xi(0)$ as shown in

Fig. 2a. The interference from multiple small cells was considered by randomly selecting a value of ξ for each interfering SBS in the range of 0–1. Signal to Interference Noise Ratio (SINR) at SBS n^* is determined by

$$\text{SINR} = \frac{P_s G_{nn^*} g_{nn^*}^2 \xi(0)\xi(0)}{\sum_{q\in Q} P_s G_{qn^*} g_{qn^*}^2 \xi(\theta(qn^*, qq^*))\xi(\theta(nn^*, qn^*)) + \sigma} \quad (1)$$

where σ is the noise power, Q is the set of interfering SBSs, and q^* is the receiving SBS for transmitting SBS q. The radio propagation and channel characteristics were modeled using 3GPP Urban Micro (UMi) and Indoor Hotspot (InH) models for outdoor environments and indoor small cell deployments, respectively. For indoor environment, the path loss between picocell and small cell was calculated using UMi O-to-I model, while the gain between the small cells was determined using the InH path loss model, assuming that all the small cells were deployed indoors. In the path loss PL calculations, both LoS and NLoS gains were considered based on the probability of LoS for the distance between the transmitting and receiving BSs.

$$PL = pPL_{LOS} + (1-p)PL_{NLOS} \quad (2)$$

where p is the probability of LoS, and PL_{LoS} and PL_{NLoS} are the LoS and NLoS components of the path loss, respectively. Probability of LoS was calculated according to [20] and for the UMi model, which was given by

$$p = min\left(\frac{18}{d}, 1\right)\left(1 - e^{\frac{-d}{36}}\right) + e^{\frac{-d}{36}} \quad (3)$$

In addition, for the InH path loss model, LOS probability was calculated as

$$p = \begin{cases} 1 & d \le 18 \\ e^{\frac{-(d-18)}{27}} & 18 < d < 37 \\ 0.5 & d \ge 37 \end{cases} \quad (4)$$

where d is the distance between the transmitting and receiving BSs. Owing to high probability of LoS connection in UDN, the multipath fading was modeled using the rician channel, in which the K factor of the rician channel was derived from the probability of LoS [21].

3.3. Distributed routing over backhaul network

Several studies on mmWave backhaul, such as [8], considered routing between the picocell and small cells based on ST protocol. These schemes considered an ST rooted at the picocell, where the size of the ST was limited by the maximum number of hops. However, in the case of dense small cells, constraining the ST size based on the number of hops or any other measure, such as path cost, in terms of delay could leave out some of the small cells without any connectivity to the core network. In contrast, the existance of an unconstrained ST for each picocell connecting all the small cells in the network could be impractical. We considered a distributed routing scheme for multihop backhaul, in which each small cell forms a neighbor relationship only with its immediately connected small cells or picocell. The path toward the picocell is determined by each small cell based on the least number of hops required. To route the backhaul traffic in this case, each small cell shares the information about the gateway picocell that it is connected to, and the required number of hops to reach the picocell of its immediate neighbors. As a user could be in the coverage range of multiple small cells, a user associates with the small cell at lowest hop-count from the picocell. However, if a single small cell does not meet the backhaul throughput requirement, multipath routing with load balancing based on link quality is considered. To this end, by assuming the transmitting power of each SBS to be constant, the backhaul path and link selection at each SBS can be considered according to the following equations.

Table 1
Simulation parameters.

Carrier frequency	60 GHz
System bandwidth	100 MHz
Max. transmitting power P_p, P_s	23, 19 dBm
Noise power	−174 dBm/Hz
Antenna gain picocell	38 dBi
Antenna gain small cell	38 dBi
UMi fading LoS, NLoS	3, 4 dB
UMi O-to-I fading	7 dB
InH fading LoS, NLoS	3, 4 dB
Traffic model	Full Buffer
Small cell density λ_s	2000/square Km
Active user density λ_u	600/square Km

$$\min_{K,L} \sum_{k=1}^{K} \sum_{l=1}^{L} P_s \quad (5)$$

$$s.t. \sum_{k=1}^{K} \sum_{l=1}^{L} \log\left(1 + SINR_k^l\right) \ge c_\kappa \quad (6)$$

where K is the number of paths used by the SBS for backhaul, L is the number of links on each path and corresponds to the number of hops required to reach the picocell, and $SINR_k^l$ is the SINR on link l of path k. Here, c_κ is the minimum required backhaul throughput. The objective in (5) is to minimize the sum power on the backhaul connection of each SBS constrained by SBS's QoS requirement in terms of backhaul capacity defined in (6). Under the fixed transmitting power assumption for each SBS, the objective in (5) minimizes the number of SBSs involved in the MPMH backhaul in addition to reducing the queuing and signal processing delay over the backhaul connection. Since the objective function in (5) is linear while the constraint in (6) is concave, the problem is not a linear or convex problem and therefore cannot be directly solved using the standard algorithms. However, as the constraint (6) only depends on the SINR, we can rewrite the optimization problem as

$$\min_{K,L} \sum_{k=1}^{K} \sum_{l=1}^{L} P_s \quad (7)$$

$$s.t. SINR_k^l \ge \gamma \quad (8)$$

where γ is the mean SINR on each link that satisfies the throughput constraint defined in (6). Now, the problem in (7) and (8) turns out to be a Linear Optimization (LP) problem and can be solved using simplex method [22].

For routing downlink traffic, picocell uses the reverse path based on source of the received packets. This routing scheme is scalable and offers alternative paths for backhaul and therefore suites the flexible UDN deployment. The routing scheme is explained in Fig. 2. The details of route computation are not in the scope of this paper but in general the requirements for our routing scheme are:

- For each small cell, there should be at least one path to the picocell.
- For each small cell, the routing scheme should provide as many low cost or node disjoint paths to the picocell as possible for load balancing and local rerouting in case of link failure.

4. Performance analysis

To analyze downlink performance of the four backhaul schemes, default parameters are configured as follows: the maximum permissible BS transmitting powers are set to 23 and 19 dBm for picocell and small cell respectively. The noise spectral density is set as −174 dBm/Hz. It is assumed that the small cells are randomly distributed within an area of radius 400m and the picocells have ideal wired backhaul to the core network. Other parameters are listed in Table 1.

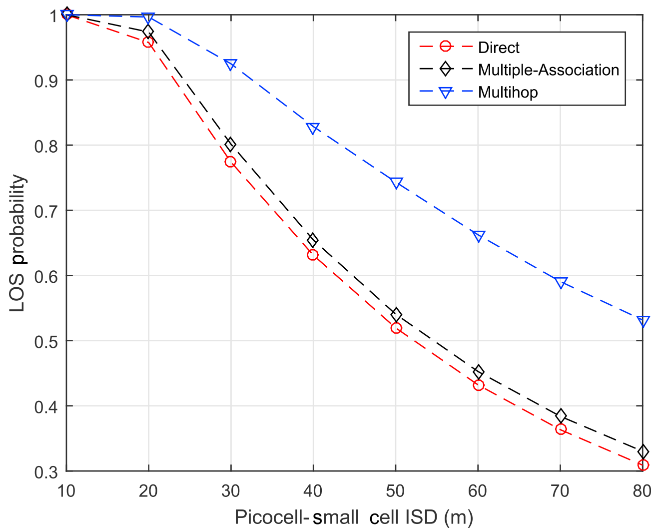


Fig. 3. LoS probability for backhaul link between small cell and picocell for different backhaul schemes.

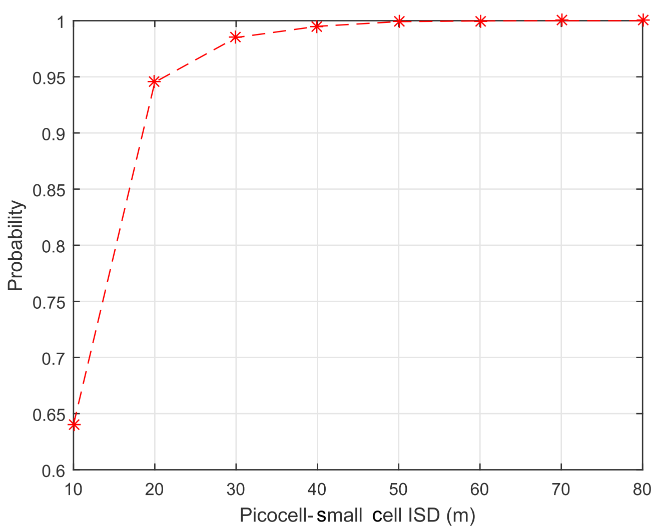


Fig. 4. Probability of finding a better LoS backhaul link between small cell and picocell multihop backhaul.

4.1. LoS probability and wired-picocell density

The performance of mmWave backhaul on the availability of LoS connection between the transmitter and the receiver. The probability of a LoS backhaul link between small cell and picocell for the direct, multiple-association and multihop schemes is compared in Fig. 3 for varying picocell-small cell ISD. Multihop scheme gives the highest probability of LoS compared to the other schemes for any given value of ISD. As the picocell density is reduced, i.e., picocell-small cell ISD is increased, the LoS probability decreases for all the backhaul schemes. There is a strong correlation between the LoS probability of direct and multiple-association schemes as is indicated by the results in Fig. 3a. This is due to the short ISD between the two small cells, as we consider that the UE is connected with the two nearest small cells in the case of multiple-association scheme. The results in Fig. 4 show that as the ISD between small cell and picocell increases, probability of finding a multihop backhaul link with better LoS compared to direct link increases. These results indicate that in UDN, the multihop mmWave backhaul schemes require less number of wired-picocells compared to direct and multiple-association schemes for the same level of backhaul performance.

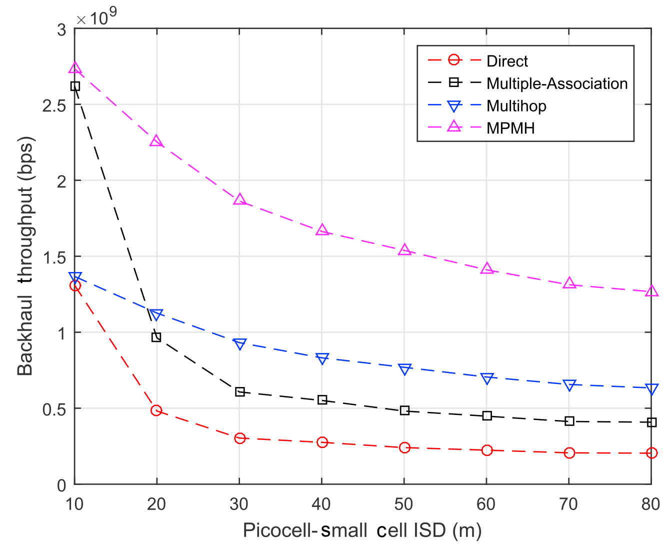


Fig. 5. Backhaul throughput performance of different backhaul schemes for outdoor small cell deployment.

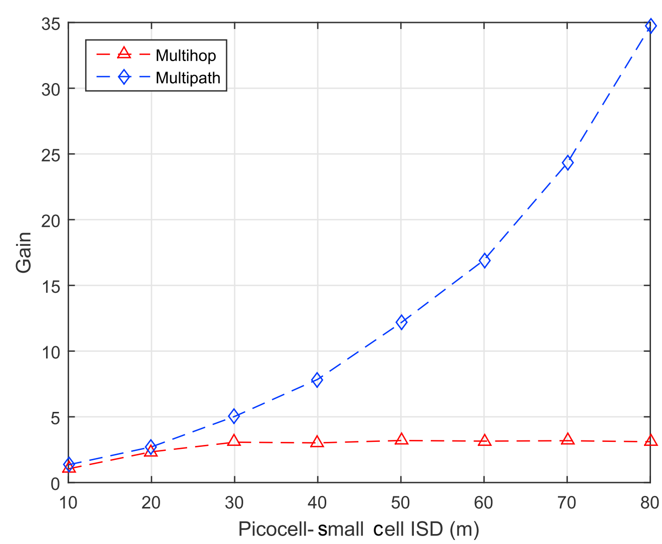


Fig. 6. Multipath and multihop gains for outdoor small-cell deployment.

4.2. Downlink rate, multipath and multihop gains

The backhaul performance of the four schemes for outdoor small cell deployment scenario is compared in Figs. 5 and 6. In Fig. 5, the backhaul throughput of different schemes is compared for varying picocell small cell ISD. The throughput decreases for all the backhaul schemes as the picocell density is reduced, i.e., ISD between picocell and small cell is increased. The decrease in throughput is due to the enhanced channel attenuation over longer backhaul link. MPMH backhaul gives the highest throughput for a given picocell density as it has better path loss compared to the other schemes because of shorter communication links and has multipath gain. For a fixed picocell-small cell ISD, the backhaul capacity of multihop and multiple-association schemes can be further improved by increasing the number of hops and connecting to more small cells, respectively. This also indicates the dependence of backhaul capacity of these schemes on the availability of small cells in the idle mode. However, in the case of multihop schemes (multihop and MPMH), a small cell can also connect to another SBS even if it is not in the idle mode, thereby sharing the backhaul capacity of that small cell with its connected UEs. The improvement in backhaul throughput in this case is due to the

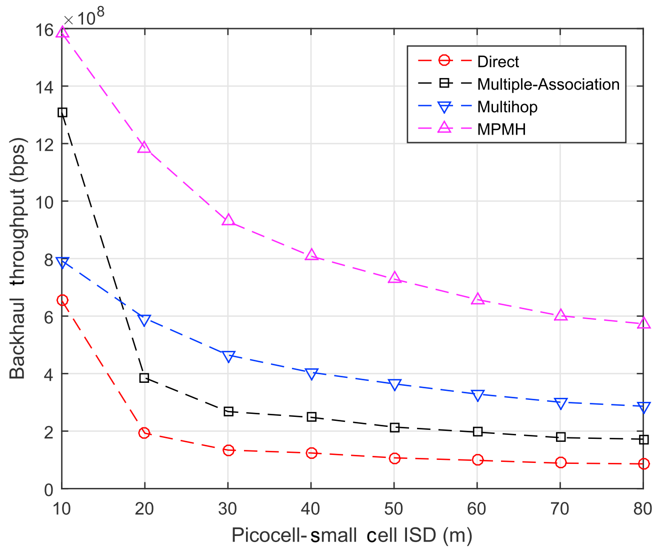


Fig. 7. Backhaul throughput performance of different backhaul schemes for indoor small cell deployment.

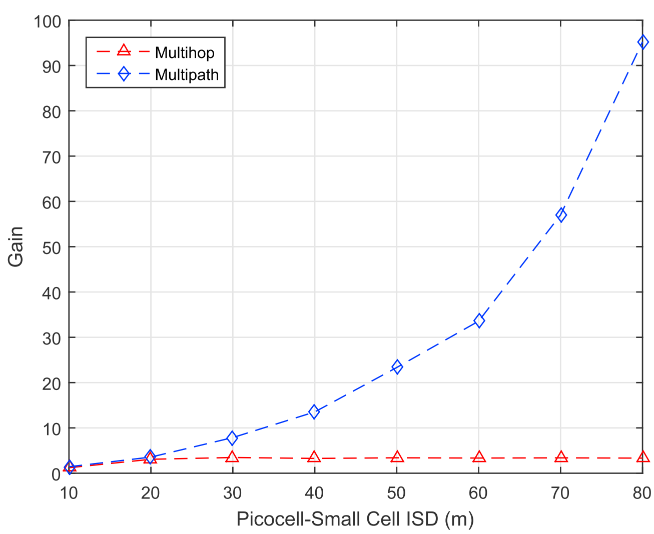


Fig. 8. Multipath and multihop gains for indoor small-cell deployment.

improved link quality over the multihop link. Fig. 6 presents the multipath and multihop gains for outdoor small cell deployment when the multihop backhaul scheme is employed. Multipath gain is calculated as the ratio between the best and worst multihop paths, in terms of throughput, that are available at a specific small cell. As the distance from the picocell increases, the diversity in various multihop paths increases; this is indicated by the increase in multipath gain in Fig. 6. In contrast, multihop gain is low and does not increase much with the picocell-small cell ISD. Multihop gain here is calculated as the ratio between the achievable backhaul throughput on multihop and direct links. As we consider a maximum of two hops, the splitting gain becomes less significant with the increase in picocell-small cell ISD due to higher channel attenuation and interference.

For the indoor small cell deployment scenario, the backhaul performance of the four schemes is presented in Figs. 7 and 8. The backhaul throughput of different schemes is compared in Fig. 7 for varying ISDs. Overall, the backhaul throughput in the case of indoor deployment is lower than outdoor small cell deployment, and it decreases as the ISD between picocell and small cell increases for all the backhaul solutions. The smaller throughput for indoor small-cell deployment is due to wall penetration losses and the absence of LoS path between the small cell and picocell BSs. The MPMH backhaul scheme gives the highest throughput for a given picocell-small cell ISD compared to other schemes even for the indoor small cell deployment scenario. Similar to the results for outdoor deployment, multiple association offers higher backhaul throughput compared to multihop when the picocell-small cell ISD is small. However, as the ISD increases, the throughput over the single-hop link decreases sharply because of high channel attenuation. Multipath and multihop gains for indoor small-cell deployment are evaluated in Fig. 8. As the distance between picocell and small cell increases, the diversity in the available multihop backhaul links increases; this is indicated by the increase in multipath gain. The multihop gain in Fig. 8 first increases with ISD but stabilizes as the splitting gain becomes almost constant for large picocell-small cell ISDs.

5. Conclusion and future work

Backhaul in UDN is a major challenge for realizing the performance goals set for 5G. In this paper, we studied mmWave wireless backhaul for an ultra-dense small cell network. We specifically investigated direct, multiple-association, multihop, and MPMH backhaul schemes for UDN in mmWave frequencies for outdoor and indoor small cell deployments. A distributed routing scheme was employed to forward the backhaul traffic over the multihop network. We compared the throughput performances of these schemes under interference limited scenarios for varying picocell densities and evaluated the LoS probability of the backhaul links for these schemes. Furthermore, the results for multihop and multipath gains were presented. The simulation results indicated that the MPMH backhaul is the most cost-effective and scalable solution and is more suited to the flexible small cell deployment in UDN than the other schemes. The results also indicated that compared to direct and multiple-association shcemes, the multihop backhaul scheme requires less number of picocells to provide the same level of backhaul capacity. The following are possible future research directions.

- MPMH backhaul affects the energy consumption of the network by increasing the traffic demand on certain SBSs and employing idle nodes to relay backhaul traffic. Thus, it is significant to study the energy efficiency of the MPMH backhaul network.
- Each intermediate node over the multihop backhaul link contributes to the processing and queuing delay; therefore, it is important to investigate the delay performance of the MPMH backhaul.
- Moreover, it is important to design path selection strategies that consider energy efficiency, in addition to backhaul delay and throughput, as it affects the overall energy consumption of UDN because of the use of smart idle mode capability.

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