Resource Allocation and Interference Management for Opportunistic Relaying in Integrated mmWave/sub-6 GHz 5G Networks

Junquan Deng, Olav Tirkkonen, Ragnar Freij-Hollanti, Tao Chen, and Navid Nikaein

The authors consider a hierarchical network control framework to address the relay and beam selection, resource allocation, and interference coordination problems. They evaluate mmWave/sub-6 GHz multi-connectivity with and without two-hop relaying in urban outdoor scenarios for different site deployment densities.

ABSTRACT

The 5G networks are envisioned to use mmWave bands to provide gigabit-per-second throughput. To extend the coverage of extreme data rates provided by mmWave technologies, we consider two-hop relaying based on D2D communication in an integrated mmWave/sub-6 GHz 5G network. Compared to single-hop multi-cell networks, two-hop D2D relaying in this network will complicate the network management. Relay selection and beam selection should be considered together as relaying in mmWave bands would use directional beamforming transmissions. MmWave/sub-6 GHz multi-connectivity has to be managed, and resources have to be allocated across frequencies with disparate propagation conditions. In this article, a hierarchical network control framework is considered to address the relay and beam selection, resource allocation, and interference coordination problems. The sub-6 GHz band is responsible for network control and for providing relatively reliable communications, while the mmWave band provides high-throughput enhancement. Opportunistic relay selection and mmWave analog beamforming are used to limit the signaling overhead. We evaluate mmWave/sub-6 GHz multi-connectivity with and without two-hop relaying in urban outdoor scenarios for different site deployment densities. MmWave/sub-6 GHz multi-connectivity with relaying shows considerable promise for reaching consistent user experience with high end-to-end throughput in a cost-effective network deployment.

INTRODUCTION

The volume of mobile traffic and the number of connected devices are predicted to increase significantly in the fifth generation (5G) networks. More spectrum, spectrum-efficient physical layer techniques, and network densification are key enablers to handle this growth. Consistent user experience is regarded as a fundamental 5G requirement [1]. With current cellular technologies, users at the cell edge suffer from poor service, even when complicated coordinated multipoint transmission technologies are applied [2]. Further densification of wireless networks using millimeter-wave (mmWave) bands, combined with massive multiple-input multiple-output and beamforming techniques, provides a framework to achieve throughput in the range of gigabits per second. However, mmWave signals are more vulnerable to blocking than sub-6 GHz signals. To achieve both high capacity and consistent user experience, mmWave infrastructure needs to be densely deployed to increase line-of-sight (LOS) probability, and to tackle the path loss and blockage problems [3, 4]. It is estimated that an intersite distance (ISD) of 75–100 m is required for full coverage in standalone mmWave deployments [5]. Deploying dense sites increases capital and operating expenditures (CAPEX and OPEX) for operators, thus increasing cost for users. To this end, extreme network densification for providing full mmWave coverage may not be viable.

A reasonable way to introduce mmWave technology is to tightly integrate an mmWave network with an existing sub-6 GHz network [6, 7]. However, in the integrated scenario, consistency of user experience is jeopardized, as a large number of users outside the mmWave coverage cannot get high throughput. MmWave coverage can be improved with relaying, by applying a multihop cellular network (MCN) concept. In [8], relay selection and interference management were investigated in an interference-limited code-division multiple access MCN. A time-division duplex frame structure for integrating infrastructure relays in mmWave with a 4G network was considered in [9]. Recently, the potential benefits of deploying mmWave relays in outdoor environments were investigated in [10]. Deploying relays in mmWave networks was shown to increase the coverage probability and end-to-end (E2E) capacity.

In 5G, network controlled device-to-device (D2D) communication is under consideration. Accordingly, D2D relaying based on cooperation between user equipments (UEs) can be used for mmWave coverage extension and to tackle inconsistent user experience. As the number of UEs increases, the probability that a cell edge user can find favorable mobile relays (e.g., LOS relays) increases, and E2E performance can be boosted by using D2D relaying transmission.

In this article, we investigate the downlink of a 5G network based on mmWave and sub-6 GHz multi-connectivity. We consider a scenario where

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UEs carried by vehicles act as relays to extend the network coverage with two-hop relaying [11]. Introducing two-hop D2D relaying into this network poses new challenges to the network control and coordination. First, mmWave communications, as well as discovery of mmWave base stations (BSs) and relays, are based on beamforming. Discovery and control signals need to be transmitted using multiple mmWave beams to cover the angular domain. The signaling overhead increases as the number of relays and beams increases. Second, in rich scattering non-line-of-sight (NLOS) scenarios, mmWaves have small channel coherence time, which induces challenges for resource allocation and control signaling. Slowly changing features, such as beam directions and LOS/NLOS/outage conditions, however, dominate relay selection and multi-connectivity, easing the challenge. Thus, selecting the best mmWave link will correlate with selecting the most stable mmWave link. Third, in a two-hop cellular network, the interference environment is complex. In addition to interference from neighboring BSs, there may be interference from nearby relays.

When considering D2D relaying, many of the current solutions are not scalable. Collecting full channel state information to a centralized controller for channel inversion requires significant signaling overhead, scaling at least with a power of the number of devices in a cell. Optimum relay selection in itself is a NP-hard problem [12], and so are the resource allocation and inter-cell interference coordination (ICIC) problems, whether formulated in terms of discrete (e.g., graph coloring) or continuous variables (e.g., power control). Applying conventional methods for these problems would require either collecting excessive amounts of information to a centralized controller, or using iterative distributed network algorithms with possibly slow convergence. Such solutions are problematic if moving or nomadic relays are considered. Aggregating mmWave and sub-6 GHz carriers adds a further spectrum management twist to the problem, as the propagation conditions on the two bands are very different.

In this article, we propose a hierarchical architecture for scalable network management to efficiently control and coordinate multi-connectivity, relay and beam selection, resource allocation, and interference management. The objective is to extend coverage and achieve consistent user experience without extreme infrastructure densification, and to reduce the control overhead for relay and beam selection.

Network Architecture and System Model

5G Integrated mmWave/Sub-6 GHz Networks

We consider integrated mmWave/sub-6 GHz networks, where mmWave hardware is added to sub-6 GHz microcells for performance enhancement. For simplicity, we do not assume a possible umbrella macro tier. The scenario is depicted in Fig. 1. The sub-6 GHz carrier is narrow compared to the mmWave carrier, but has more reliable and continuous coverage. The mmWave carrier has unreliable coverage, suffering from poor signal quality when signals are blocked. The sub-6 GHz and mmWave carriers thus complement each other in a multi-connectivity phantom cell [13]. D2D relaying is enabled on both mmWave and sub-6 GHz bands. A subset of idle state user equipments (UEs), for example, ones attached to parked vehicles, are selected as relay candidates and would be moved to a relay candidate state. The sub-6 GHz resources may be used for signaling, network control and data communication for UEs with poor signal quality, and to manage mmWave links. The wideband mmWave carrier would be used by the destination UEs and selected relays that have good channels.

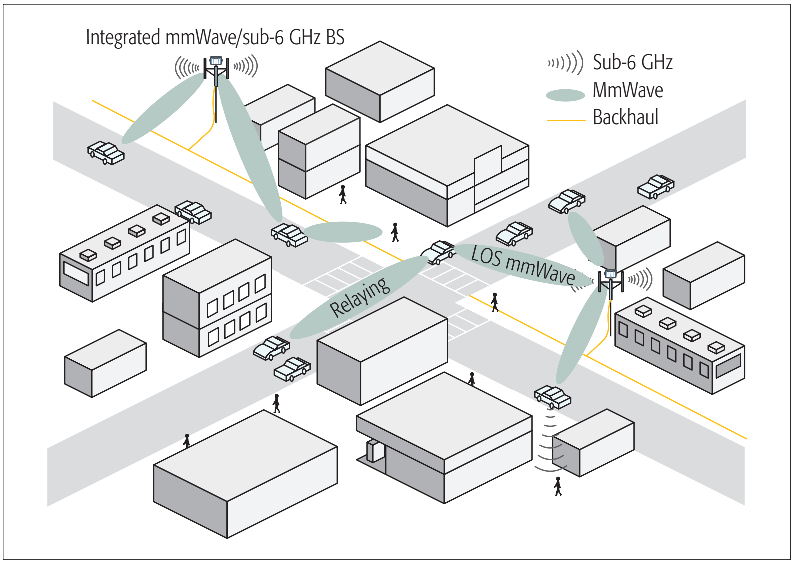

Figure 1. Relaying in the integrated mmWave/sub-6 GHz 5G network.

Channel Modeling and Beamforming for mmWave

Channel modeling and coverage estimation for mmWave networks can be found in [3, 5]. The extremely high mmWave frequencies result in large path loss due to small antenna apertures, whereas the short wavelengths also make it possible to integrate numerous array elements in a small area. By using directional beamforming transmissions, the received signal power can be improved while simultaneously spreading less interference outside the direction of the intended receiver. Although directional transmissions can compensate path loss in mmWave frequencies, the coverage area is still limited without the LOS condition. A probabilistic mmWave LOS/NLOS/outage model in urban scenarios was discussed in [3]. A typical mmWave link would have a 20 dB larger path loss than a traditional sub-6 GHz link, and mmWave LOS and NLOS links may have a 30 dB path loss difference [3]. For outdoor LOS links, the effect of multipath scattering components is assumed to be marginal since the power of NLOS components is usually 20 dB weaker than the LOS component [4] due to a lack of diffraction. LOS condition is a spatial stochastic process caused by random obstacles. Nearby UEs enjoy the same LOS condition with a high probability. To capture this spatial LOS correlation, an exponential correlation model with a LOS correlation distance that depends on the size of obstacles is used to generate LOS conditions.

MmWave channels differ from traditional sub-6 GHz channels, thus requiring new principles for

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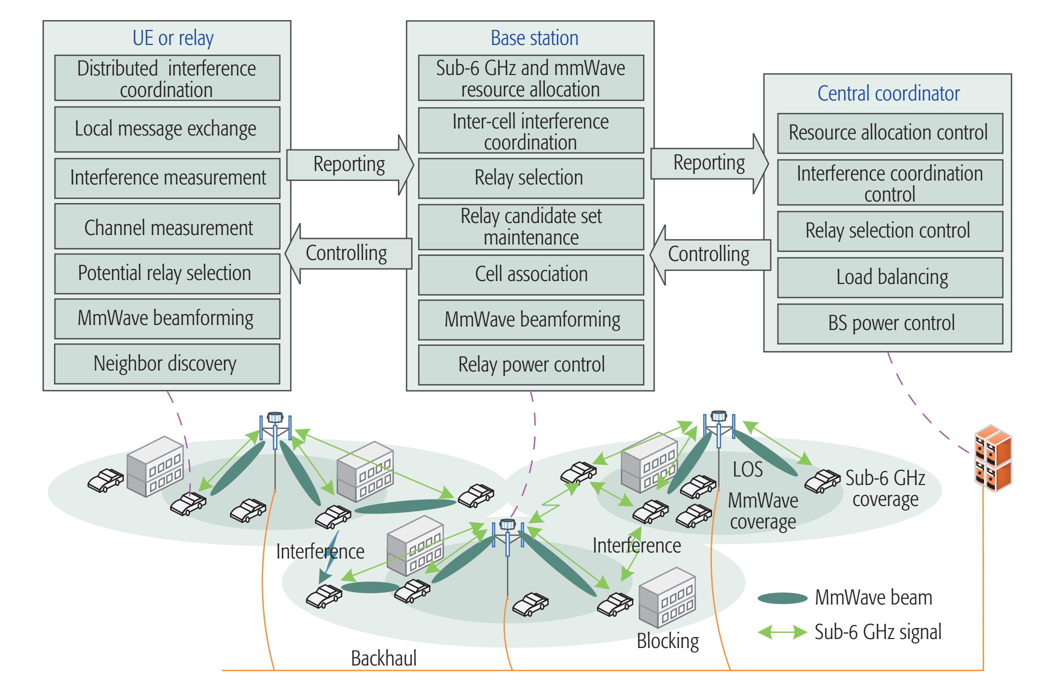


Figure 2. A hierarchical control framework for relaying-enabled integrated mmWave/sub-6 GHz networks.

wireless cooperative communications and network architecture design. First, large path loss and penetration loss on mmWave bands mitigate interference significantly. Second, thanks to sparsity in the angular and delay domains in mmWave channels, analog beamforming using narrow beams can improve power gain while requiring less channel estimation overhead compared to digital beamforming, and is a low-complexity option for mmWave communications. Third, directional mmWave transmissions will provide a new degree of freedom for link scheduling. Last, avoiding blocking is important for the mmWave network design. In this context, D2D relaying can significantly increase E2E LOS probability, making it a powerful method for blocking avoidance in mmWave networks.

Hierarchical Control Framework for Multi-Connectivity and D2D Relaying

Scalability is a key feature for an operational complex network. For the integrated mmWave/sub-6 GHz network, we define scalability as the ability to handle a large amount of high-throughput connections across multiple cells with limited control overhead and CAPEX/OPEX. Scalability is a general problem for multihop wireless networks. Due to the complicated interference situation, traditional multihop wireless networks do not scale well [14], as control overhead increases and user quality of service (QoS) drops significantly when the number of nodes, mobility, and traffic load increase. Conventional single-hop cellular networks are scalable in the sense that they can offer interference management and minimum QoS. However, in 5G, a single-hop paradigm with extreme mmWave network densification is challenging in terms of CAPEX/OPEX. In contrast, a two-hop paradigm with the integrated mmWave/sub-6 GHz network may be feasible to provide high-throughput services with consistent user experience, as relaying management with two hops is tractable and BS deployment cost is reduced.

To implement two-hop relaying, cell association, relay and beam selection, resource allocation, and interference coordination need to be considered together. Cell association in such a multi-connectivity network with D2D relaying is more complex than in a single-hop cellular network, especially for cell edge UEs. The direct downlink is characterized by both sub-6 GHz and mmWave path losses. Since sub-6 GHz path loss is more stable, cell association should be based on sub-6 GHz path loss to achieve mobility robustness, possibly subject to load balancing considerations. Meanwhile, relay and beam selection should not only consider the target E2E performance, but also the inter-cell interference. Multi-user resource allocation is also challenging due to heterogeneity in the resources and the links to be scheduled. We consider a scalable hierarchical control framework to address the above mentioned challenges. The network control is based on network state information including traffic loads, link qualities, and the measured interference. In a large-scale network, it is difficult for a centralized controller to access all network state information and make control decisions in a timely manner due to the delay and overhead in transport of network state information. A hierarchical control framework that splits network control into different levels according to different delay requirements is necessary. Figure 2 describes the proposed control framework, which consists of three levels of control: a logical central coordinator, local BS controllers, and distributed coordination in the cooperative D2D network. To limit the complexity of the NP-hard networking problems and the related excessive signaling, the following principles are followed in this hierarchical framework:

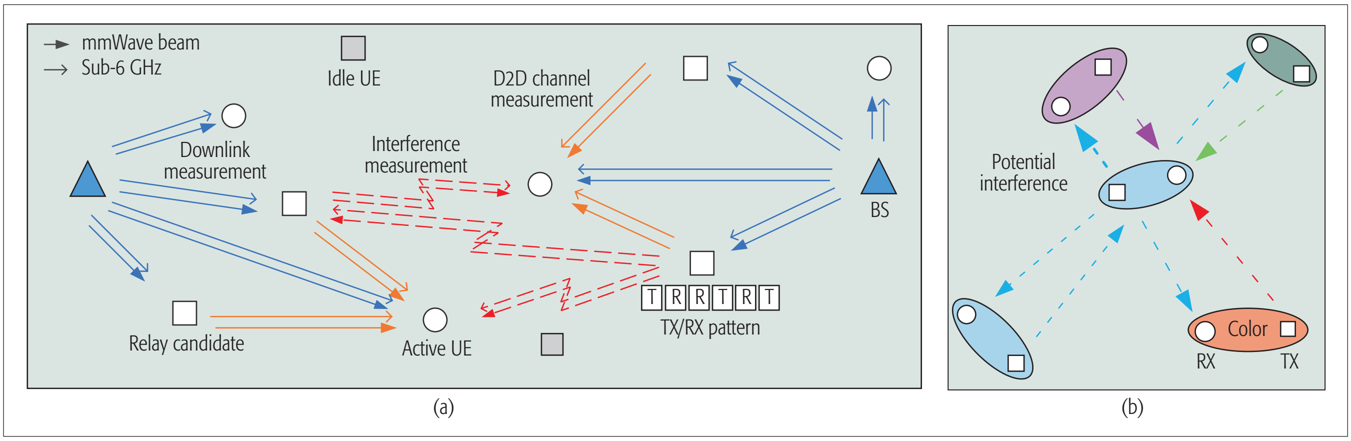


Figure 3. a) A discovery/measurement framework for the integrated mmWave/sub-6 GHz networks with D2D relaying; b) local interference graph constructed by interference measurement. Each relay-to-UE link uses a specific fraction of the D2D resources, indicated by a color. Here the central blue D2D pair and the purple D2D pair are close neighbor links, so they should not use the same color to avoid strong interference.

- The BS-to-relay hop always uses mmWave resources, while the relay-to-UE (i.e., D2D) hop can use mmWave or sub-6 GHz resources.
- A limited set of relay candidates, typically with LOS to a BS, is selected by the BS.
- Destination UEs at the cell edge select a small set of potential relays from the relay candidates and report this set to the BS.
- The potential relays are communicated to the BS, and the BS makes the decision on relay selection and allocates resources to the destination UEs and the relays.
- Interference management for relaying is performed via limiting the set of relay candidates by the BS controller, and by distributed interference coordination locally in the D2D network.

As shown in Fig. 2, the central coordinator collects global network state information reported by local BS controllers and sets high-level parameters that are used by the lower-level entities. Information collected from BSs includes:

- The number of destination UEs and their traffic load
- The number of cell edge destination UEs and their traffic load
- Number of available relays.

The central control functionalities include determining relay selection parameters (e.g., rules for selecting relay candidates, rules for selecting potential relays for a UE, and the maximum number of active D2D relaying links); interference coordination parameters (number of resources, interference coordination thresholds); and resource allocation parameters (e.g., scheduling metric). The central coordinator also controls the sets of node identification (ID) codes (for UEs and relays) used inside each cell so that neighboring cells have separable sets of ID codes.

The local BS controllers are responsible for:

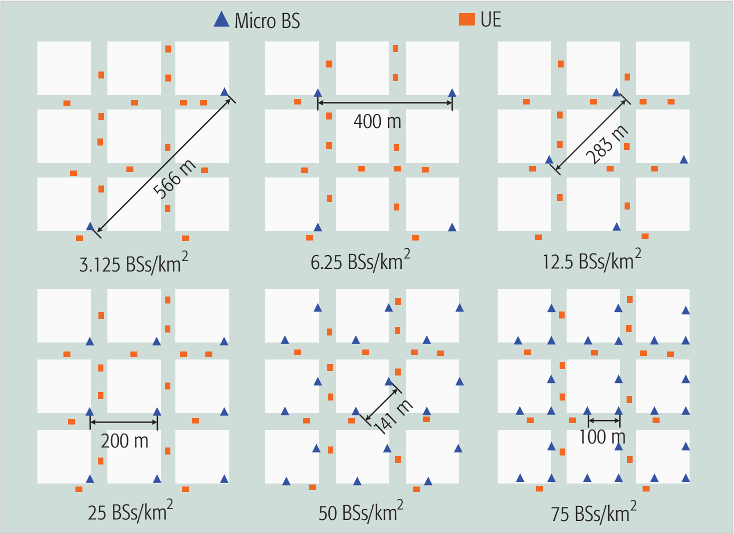
- Maintaining the set of candidate relays, allocating ID codes to them
- Collecting channel measurements for BS-to-relay, relay-to-UE, and BS-to-UE links
- Performing relay and beam selection
- Resource allocation for UEs and relays using the scheduling metric defined by the central coordinator
- ICIC by dividing resources between cell center UEs, cell edge UEs, and relays.

The lowest-level control is distributed in the D2D network of relay candidates and destination UEs. Neighbor discovery is performed, where UEs find D2D neighbors periodically to activate links and measure interference. Downlink and D2D channel qualities and interference powers are measured on both sub-6 GHz and mmWave bands. These measurements are used for relay and beam selection and interference coordination. Cell edge UEs select potential relays based on these measurements, and communicate to the BS. UEs and relays may perform fast local interference coordination by exchanging interference information between neighbor D2D links.

The timescales of the different control layers differ according to the control targets and how fast the network changes. The most crucial large-scale effect of the mmWave network is the variation of the LOS/NLOS/outage conditions. If LOS correlation distance is 10 m and the UEs move at a speed of 30 km/h, the LOS condition may change once per second. The above mentioned control functions on BSs, relays, and UEs should be able to respond to these changes within some tens of milliseconds. While these low-level controllers should be able to deal with the fast and microscopic changes of the network, the high-level central coordinator is responsible for dealing with the macroscopic changes of the network on a timescale of seconds.

Scalable Relay and Beam Discovery and Channel Measurement

In the relaying-enabled network, a high number of measurements have to be performed for interference coordination, and relay and beam selection. The amount of measurements is proportional to the number of beams and size of the relay candidate set. A fast and scalable discovery/measurement framework is essential for two-hop relaying. The discovery/measurement framework is depicted in Fig. 3a. We utilize the transmission/reception (TX/RX) silencing patterns proposed in [15]. Each relay or UE in an area has a unique TX/RX pattern, and transmits a beacon signal



(a)

Manhattan grid in 1200 m × 1200 m		
Carrier frequency	mmWave	28 GHz
	Sub-6 GHz	5.9 GHz
Bandwidth	mmWave	500 MHz
	Sub-6 GHz	40 MHz
Path loss model	mmWave LOS	$61.4 + 20 \times \log_{10}(d)$ [3]
	mmWave NLOS	$72.0 + 30 \times \log_{10}(d)$ [3]
	Sub-6 GHz	WINNER II B1
LOS probability	Same street	LOS model in [3]
	Different streets	NLOS/outage
Maximum TX power	mmWave	BS: 24 dBm UE: 21 dBm
	Sub-6 GHz	BS: 30 dBm UE: 24 dBm
LOS correlation distance		10 m
MmWave antenna array		BS: 8 × 8 UPA UE: 8 × 1 UCA
Sub-6 GHz antenna		Omnidirectional
MmWave beamforming		Analog, fixed beams
Number of beams		BS: 16 UE: 8
Resource scheduling		Proportional fair (PF)

(b)

Figure 4. a) Six BS deployment scenarios with different ISDs and correspondingly different BS densities in a Manhattan grid; b) simulation parameters.

periodically. UEs will try to decode the beacons sent by neighbors and estimate the link quality and interference power. The beacon signal will encode some information including node ID, beam ID, and interference avoidance requests. By controlling the number of relay candidates and the periods of beacons according to the network state, fast and scalable neighbor discovery and network measurements can be achieved. The signaling procedure for relaying includes:

1. BSs transmit sub-6 GHz discovery signals using omnidirectional broadcasts, and directional mmWave discovery signals using a set of beams.
2. Both destination UEs and idle UEs conduct downlink channel measurements on sub-6 GHz and mmWave bands, and associate with the best BS on sub-6 GHz. The best mmWave TX-RX beam pairs are found for the selected BS.
3. An idle UE will report to its serving BS if the downlink channel quality using optimal beam pairs is larger than a threshold (determined by the central coordinator), reporting that it may act as a relay.
4. BSs update and inform the candidate sets. Each candidate in these sets gets an ID code.
5. Candidate relays transmit mmWave beams and sub-6 GHz discovery signals for the destination UEs to perform relay and beam discovery, and D2D channel quality measurements. Relay and beam IDs are embedded in these transmissions, enabling identification and collision resolution.
6. Cell edge UEs select potential relay candidates and their best beams based on D2D measurements on both sub-6 GHz and mmWave bands. UEs send results to the selected potential relays together with their ID codes. These transmissions may use a discovery code to ensure that they are heard by candidate relays in neighboring cells. Note that the best relay may be in another cell. Due to the cell selection principle, such a relay is not selected.
7. The relay candidates inform the local BS if they are selected to be potential relays by cell edge UEs, and report the related channel qualities.
8. The BSs select relays for their cell edge UEs, and perform joint mmWave/sub-6 GHz resource allocation and the beam assignment for direct, BS-to-relay, and relay-to-UE links.

Reporting from UEs or relays and informing from BSs can be performed on the sub-6 GHz band to provide reliable network control. Signaling overhead is controlled by limiting the number of candidate relays and the number of potential candidate relays.

Graph-Based Methods for Relay Selection, Resource Allocation, and Interference Coordination

Graph coloring can be used to address channel assignment and interference coordination problems in wireless networks. Using an interference graph to model the interaction between neighbor links enables the controller to address relay and beam selection, resource allocation, and interference coordination in a unified way. However, a centralized graph coloring method would require the central coordinator to gather all interference information from the network for each scheduling decision. This would not be a scalable solution. To achieve scalability, we consider a distributed method for interference coordination.

Definition of Neighbor Links: We define two links to be neighbors if the interference from one link to the other is larger than a threshold compared to the wanted signal power for the other. Using the same radio resource for neighboring links leads to a conflict. When the links are dense in space, we usually cannot solve all conflicts, but the strongest interference can usually be avoided. Figure 3b shows a local interference graph for one D2D relaying link.

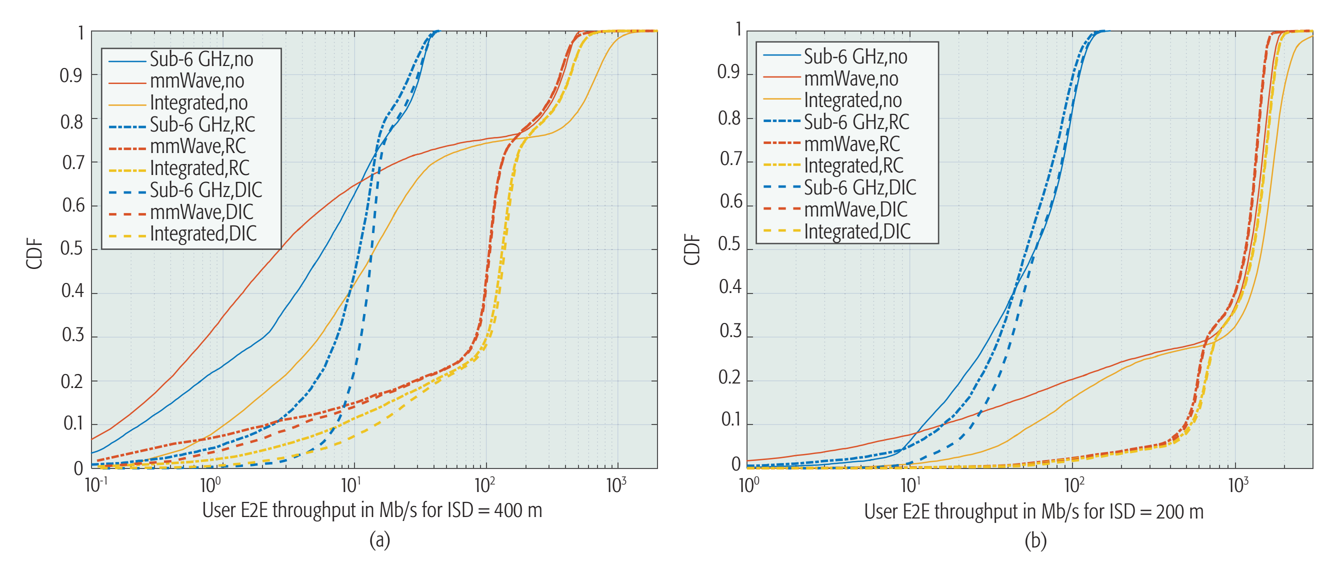


Figure 5. a) CDF of user E2E throughput in standalone sub-6 GHz, standalone mmWave and the proposed integrated mmWave/sub-6 GHz (Integrated) deployments with ISD = 400 m, for no relaying, relaying with random coloring (RC-relaying), and relaying with distributed interference coordination (DIC-relaying); b) CDF of user throughput in sub-6 GHz, mmWave, and integrated deployments with ISD=200 m, for no relaying, RC-relaying, and DIC- relaying.

Resource Colors: Resources reserved for D2D relaying are partitioned into fractions, called colors. A D2D link uses one such fraction for relaying. For both sub-6 GHz and mmWave resources, frequency-division multiple access can be used, and resources may be partitioned in both the frequency and time domains. The number of partitions (colors) in time and/or frequency, and the resources used for relaying are determined by the central coordinator.

Relay Selection: According to the reported channel qualities, the local BS controller selects and assigns suitable relays for cell edge UEs, considering the utility and priority for each UE. UEs that cannot benefit from relaying are served with a direct downlink. The relay candidate set is updated by deleting relays that cause too many conflicts on the local interference graph.

Resource Allocation: Both sub-6 GHz and mmWave resources may be allocated to a link using carrier aggregation. In principle, UEs or relays with good mmWave channels would not use sub-6 GHz resources. The scarce sub-6 GHz resources are allocated to those cell edge UEs that cannot find a proper relay, or to relay-to-UE transmissions. Two methods may be used for allocating resources to relaying transmissions.

Random Coloring (RC): The resources used for relay-to-UE transmissions are chosen without interference information. Each relay uses a randomly selected fraction of the resources.

Distributed Interference Coordination (DIC): Interference avoidance requests can be used to coordinate interference. UEs that are victims of strong interference from neighboring D2D links calculate improvements in channel quality if interferers with the same color were absent. For this, the UE has measured interference powers of the interfering relays during step 5 of the procedure described earlier. When the improvement is larger than a threshold, it sends an interference avoidance request directly to the interferer. The interferer has information of the channel qualities experienced by its served UE on all resource colors, not only the one used for its communication. The interferer evaluates the change of channel quality on its own serving link when changing the color, compares this to the improvement experienced by the interference victim, and chooses a color that optimizes a local objective (e.g., sum throughput or fairness for these local UEs). This distributed interference avoidance is fast as it requires only lightweight message exchange and can be performed locally in one iteration.

Performance Evaluation

We evaluate the performance of mmWave/sub-6 GHz multi-connectivity and D2D relaying in Manhattan scenarios. Six different ISDs are considered, as depicted in Fig. 4a. UEs are uniformly distributed along the streets, with 2 destination UEs and 12 idle UEs per 100 m on average. As ISD decreases, the number of destination UEs associated with each cell will decrease. No beamforming is used for sub-6 GHz signals. Actual beam patterns are used to calculate the received and interference powers in the mmWave band. For NLOS channels, beamforming gains are calculated according to multi-path component angles. Cell edge UEs can use either sub-6 GHz or mmWave relaying depending on their channel qualities. Simulation parameters can be found in Fig. 4b. Relay selection, resource allocation, and interference coordination are performed based on the current observed network state from measurements. These functions change the network-level interference and affect the observable network state. For this, the simulation is carried out in three steps. First, only direct downlink transmissions are performed, and resources are allocated without interference information in simulation initialization. Second, based on the observed network state from the first step, BSs select relays for UEs. Uncoordinated RC is used for relaying transmissions. Third, DIC is performed independently in sub-6 GHz and mmWave bands based on the

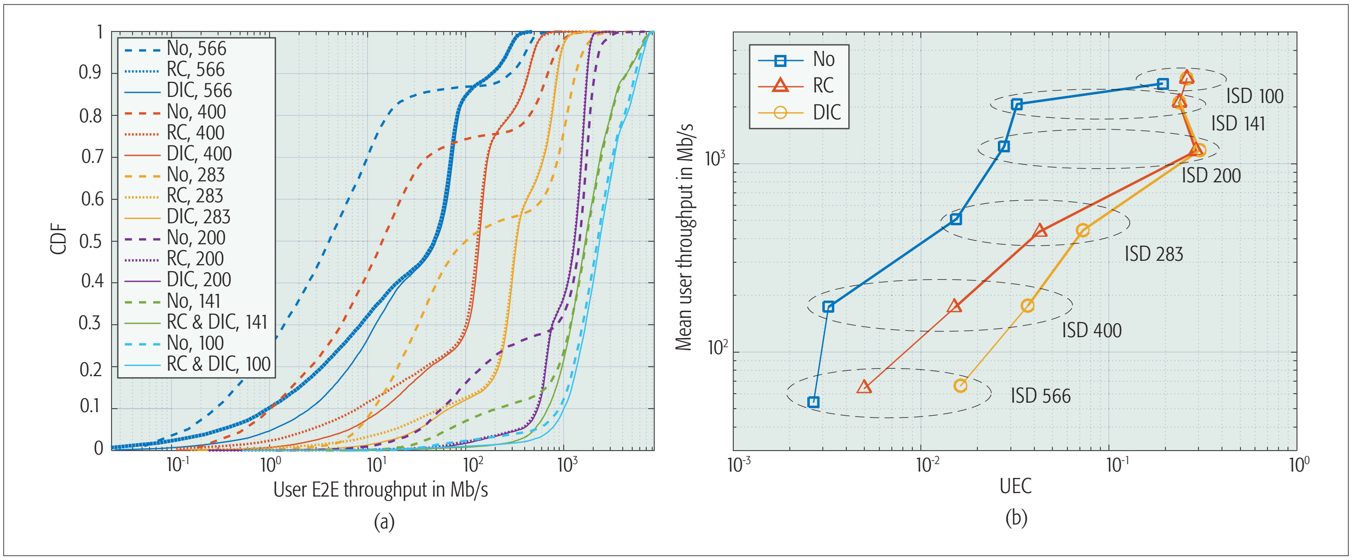


Figure 6. a) CDF of user E2E throughput in the integrated mmWave/sub-6 GHz deployment for six ISD alternatives; b) 2D plot of UEC vs. mean throughput in the integrated mmWave/sub-6 GHz deployment for six ISD alternatives, using a log-log scale.

second step network state. E2E throughputs for destination UEs in these three steps are collected to evaluate multi-connectivity, D2D relaying, and DIC gains. Overhead for relay and beam discovery and selection is taken into consideration by subtracting the amount of resources needed for signaling. We assume that data transmissions always use the best beam.

In Fig. 5 we compare the performance of the integrated mmWave/sub-6 GHz deployment and the standalone mmWave deployment. For ISD = 400 m, results can be found in Fig. 5a. User experience is inconsistent in standalone mmWave deployment without relaying. About 24 percent of users can achieve throughput above 100 Mb/s, while 65 percent have throughput below 10 Mb/s. Multi-connectivity in the integrated deployment can improve both cell edge and mean performance, as reliable sub-6 GHz resources are given to cell edge UEs while more mmWave resources are allocated to cell center UEs. RC relaying further boosts the cell edge and mean performance, with 70 percent users above 100 Mb/s for integrated deployment and 60 percent for standalone mmWave. Multi-connectivity combined with RC relaying in the integrated deployment achieves 170 Mb/s mean throughput, compared to 140 Mb/s in standalone mmWave. Using DIC relaying further improves cell edge performance compared to RC relaying. For example, the 5th percentile performance is increased from 3 to 8 Mb/s for the integrated deployment. For ISD = 200 m in Fig. 5b, user experience consistency is improved. About 70 percent of users now can find a good BS in the mmWave carrier, while the remaining 30 percent can benefit from multi-connectivity and relaying.

In Fig. 6 integrated deployment performance is reported for the six considered scenarios. CDFs of user throughput are reported in Fig. 6a. For ISD = 100 m, almost all users enjoy mmWave service, and 95 percent of UEs can achieve throughput above 500 Mb/s without relaying, vs. 97 percent with RC relaying. For ISD = 141 m, 87 vs. 95 percent, and for ISD = 200 m, 72 vs. 92 percent achieve this rate. For larger ISDs, peak rates are compromised to provide consistency, and resources are shared by more UEs in each cell. Thus, for ISD = 283 m, 42 vs. 37 percent, for ISD = 400 m, 8 vs. 5 percent, and for ISD = 566 m, 2 vs. 0 percent can reach 500 Mb/s. With larger ISD, a progressively larger fraction of UEs have low throughput due to the absence of good mmWave channels. Relaying improves the throughput of a significant fraction of these users. In the scenarios with the largest ISD, users are roughly divided into three classes: users with direct mmWave service, users with two-hop mmWave service, and users with sub-6 GHz service from the relays. It can also be observed that the larger the cells, the more relative gain can be achieved from DIC over RC. As the network becomes denser, DIC and uncoordinated RC have almost the same performance. For the two smallest ISDs, RC and DIC results are virtually overlapping. Interference conflicts occur mainly in sub-6 GHz resources, while there is less interference in the mmWave carrier. Due to directivity, interference spreads less in mmWave than in sub-6 GHz. In denser networks, most of the D2D links can use mmWave resources. Accordingly, there is less need for interference coordination between D2D links and less gain if it is done.

To characterize cell edge performance, we define a user experience consistency (UEC) metric as the ratio of the 5th percentile and mean throughput. In Fig. 6b, integrated deployment UEC is reported against mean throughput. In general, relaying methods (with RC or DIC) significantly improve UEC, except in the densest network. For larger ISDs (283 to 566 m), DIC outperforms RC, due to an improvement in cell edge throughput without mean throughput loss. The absolute value of cell edge throughput is low in these larger cells. This is a consequence of the dramatic throughput differences between the majority of users that are served with the sub-6 GHz connection, and the minority with mmWave service. Relaying can do much to improve the service of the majority in these scenarios, improving the 5th percentile throughput by allocating a part of mmWave resources to UEs that are blocked on the direct mmWave downlink but have a good two-hop mmWave connection from the BS.

The UEC curve for the denser deployments shows a zigzag behavior. This is likely due to different characteristics of the deployments, as depicted in Fig. 4a. With ISD 141, 283, 400, and 566 m, users at the cell edge are equally close to four BSs, whereas with ISD 100 and 200 m, they are equally close to two BSs. This translates to a lower path diversity for cell edge users with ISD 100 and 200 m, and accordingly a larger relaying gain. It is noteworthy that a network with ISD 200 m (25 BSs/km^2) using relaying can achieve nearly the same performance in the throughput-UEC plane as one with ISD 100 m (75 BSs/km^2) and without relaying.

Conclusion

We have considered two-hop downlink D2D relaying in an integrated mmWave/sub-6 GHz network as a method to avoid blocking and extend coverage for mmWave communications. Relaying, combined with coordinated resource allocation over the two carriers, improves the data rates experienced at the cell edge, and accordingly leads to a consistent user experience. We have considered a hierarchical control framework to address these network management problems related to mmWave/sub-6 GHz multi-connectivity and D2D relaying. The network control and measurement overheads are limited by selecting relay candidates opportunistically and limiting the sizes of relay candidate sets. We have considered distributed interference coordination to coordinate relaying transmissions. System-level simulation in urban microcell scenarios illustrates that using D2D relaying in a network with 25 BSs per km^2, one can reach the same cell edge performance as in a three times denser deployment without relaying. With larger cells, the relative gain of D2D relaying for cell edge users is larger than in small cells, and interference coordination becomes important, especially in the sub-6 GHz band. For a standalone mmWave network, relaying gains are on the same level. However, when ISD becomes larger than 400 m, a significant fraction of users lack proper two-hop mmWave connectivity. Two-hop relaying with mmWave/sub-6 GHz multi-connectivity can improve both cell edge and mean user performance for these larger cells. The main challenge in the discussed method lies in finding proper incentives for UEs to act as relays. In this context, future work on the energy efficiency of mmWave networks with relaying is needed.

Two-hop relaying with mmWave/sub-6GHz multi-connectivity can improve both cell-edge and mean user performance for these larger cells. The main challenge in the discussed method is in finding proper incentives for UEs to act as relays. In this context, future work on energy efficiency of mmWave networks with relaying is needed.

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References

[1] NGMN Alliance, "NGMN 5G White Paper," Mar. 2015.
[2] M. Sawahashi *et al.*, "Coordinated Multipoint Transmission/Reception Techniques for LTE-Advanced (Coordinated and Distributed MIMO)," *IEEE Wireless Commun.*, vol. 17, no. 3, June 2010, pp. 26–34.
[3] M. Riza Akdeniz *et al.*, "Millimeter Wave Channel Modeling and Cellular Capacity Evaluation," *IEEE JSAC*, vol. 32, no. 6, June 2014, pp. 1164–79.
[4] H. Zhao *et al.*, "28 GHz Millimeter Wave Cellular Communication Measurements for Reflection and Penetration Loss in and around Buildings in New York City," *Proc. IEEE ICC*, June 2013, pp. 5163–67.
[5] T. Bai *et al*, "Coverage and Rate Analysis for Millimeter-Wave Cellular Networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 2, Feb. 2015, pp. 1100–14.
[6] M. M. Kassem *et al.*, "Future Wireless Spectrum below 6 GHz: A UK Perspective," *Proc. IEEE DySPAN*, Sept. 2015, pp. 59–70.
[7] H. Shokri-Ghadikolaei *et al.*, "Millimeter Wave Cellular Networks: A MAC Layer Perspective," *IEEE Trans. Commun.*, vol. 63, no. 10, Oct. 2015, pp. 3437–58.
[8] L. B. Le *et al.*, "Multihop Cellular Networks: Potential Gains, Research Challenges, and a Resource Allocation Framework," *IEEE Commun. Mag.*, vol. 45, no. 9, Sept. 2007, pp. 66–73.
[9] K. Zheng *et al.*, "10 Gb/s HetNets with Millimeter-Wave Communications: Access and Networking Challenges and Protocols," *IEEE Commun. Mag.*, vol. 53, no. 1, Jan. 2015, pp. 222–31.
[10] S. Biswas *et al.*, "On the Performance of Relay Aided Millimeter Wave Networks," *IEEE JSAC*, vol. 10, no. 3, Apr. 2016, pp. 576–88.
[11] A. Osseiran *et al.*, "Scenarios for the 5G Mobile and Wireless Communications: The Vision of the METIS Project," *IEEE Commun. Mag.*, vol. 52, no. 6, May 2014, pp. 26–35.
[12] R. Madan *et al.*, "Energy-Efficient Decentralized Cooperative Routing in Wireless Networks," *IEEE Trans. Autom. Control*, vol. 54, no. 3, Mar. 2009, pp. 512–27.
[13] H. Ishii *et al.*, "A Novel Architecture for LTE-B: C-Plane/U-Plane Split and Phantom Cell Concept," *Proc. IEEE GLOBECOM Wksp.*, Dec. 2012, pp. 624–30.
[14] I. F. Akyildiz *et al.*, "A Survey on Wireless Mesh Networks," *IEEE Commun. Mag.*, vol. 43, no. 9, Sept. 2005, pp. S23–30.
[15] E. Tiirola *et al.*, "On the Design of Discovery Patterns for Half-Duplex TDD Nodes Operating in Frame-Based Systems," *Future Network and Mobile Summit*, July 2013, pp. 1–9.

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