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

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Abstract

Future fifth generation (5G) networks are envisioned to use millimeter wave (mmWave) bands to provide Gbps throughput. To extend the coverage of extreme data rates provided by mmWave technologies, we consider two-hop relaying based on device-to-device (D2D) communication in an integrated mmWave/sub-6GHz 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 is based on directional transmissions. MmWave/sub-6GHz 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-6GHz band is responsible for network control and for providing 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-6GHz multi-connectivity with and without two-hop relaying in urban outdoor scenarios for different site deployment densities. MmWave/sub-6GHz multi-connectivity with relaying shows considerable promise for reaching consistent user experience with high end-to-end throughput in a cost-effective network deployment.

I. Introduction

The volume of mobile traffic and the number of connected devices are predicted to increase significantly in future fifth generation (5G) networks. More spectrum, spectrum-efficient physical layer techniques, and network densification are key enablers to handle these growths. Consistent user experience is regarded as a fundamental 5G requirement [1]. With current cellular technologies, users at cell edge suffer from poor service, even when complicated coordinated multi-point 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 Gbps. However, mmWave signals are more vulnerable to blocking than sub-6GHz 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 pathloss and blockage problems [3], [4]. It is estimated that an inter-site distance (ISD) of 75-100 m is required for full coverage in standalone mmWave deployments [5]. Deploying dense sites increases capital and operating expenditure (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 a mmWave network with an existing sub-6GHz 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 multi-hop 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 is considered in [9]. Recently, the potential benefits of deploying mmWave relays in outdoor environments were investigated in [10]. Deploying relays in mmWave networks is 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 (UE) can be used for mmWave coverage extension and to tackle inconsistency of 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-6GHz multi-connectivity. We consider a scenario where UEs carried by vehicles act as relays to extend the network coverage with two-hop relaying [11]. Introducing two-hop D2D relaying into a network poses new challenges to network control. First, mmWave communications, as well as discovery of mmWave base stations (BS) 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. Selecting the best mmWave link correlates 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-6GHz 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 protocol architecture for scalable network management, to control 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.

II. Network Architecture and System Model

A. 5G integrated mmWave/sub-6GHz networks

We consider integrated mmWave/sub-6GHz networks where mmWave hardware is added to sub-6GHz micro-cells for performance enhancement. For simplicity, we do not assume a possible umbrella macro tier. The scenario is depicted in Fig. 1. The sub-6GHz 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-6GHz and mmWave carriers thus complement each other in a multi-connectivity phantom cell [13]. D2D relaying is enabled on both mmWave and sub-6GHz bands. A selected subset of idle state UEs, e.g. ones attached to parked vehicles, are selected as relay candidates and would be moved to a relay candidate state. The sub-6GHz resources are used for signaling, network control and data communication for UEs with poor signal quality, and to manage mmWave links. The wide-band mmWave carrier would be used by the active UEs and selected relays which have good channels.

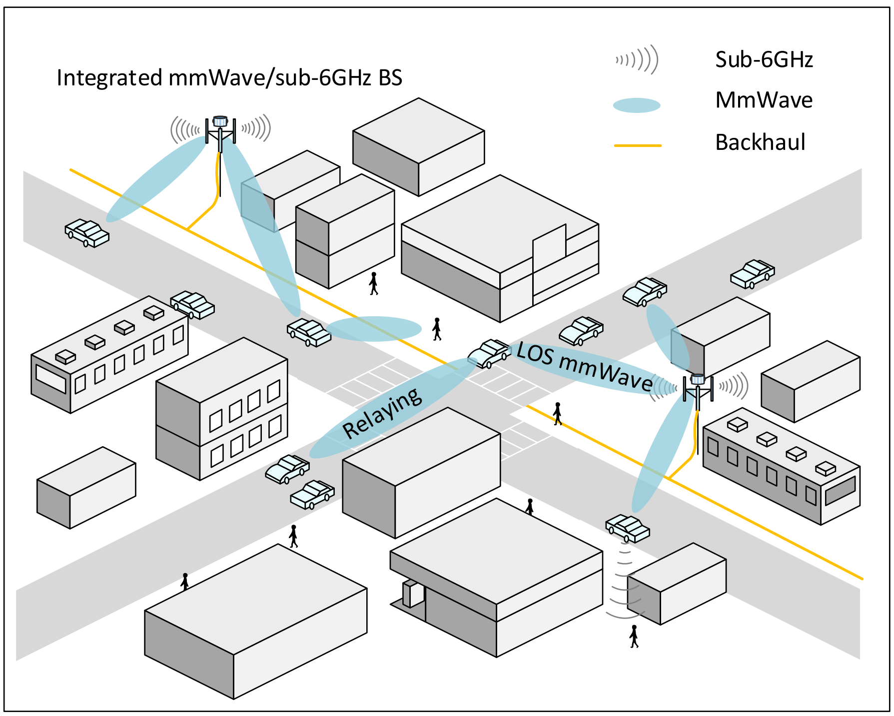


Figure 1. Relaying in the integrated mmWave/sub-6GHz 5G network.

B. Channel Modelling and Beamforming for mmWave

Channel modeling and coverage estimation for mmWave networks can be found in [3], [5]. The extremely high mmWave frequency results in large pathloss due to small antenna aperture, whereas the short wavelength also makes 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 pathloss in mmWave frequencies, coverage is still limited without LOS. A probabilistic mmWave LOS/NLOS/outage model in urban scenarios is discussed in [3]. A typical mmWave link would have a 20 dB larger pathloss than a traditional sub-6GHz link, and mmWave LOS and NLOS links may have a 30 dB pathloss difference [3]. For outdoor LOS links, the effect of multipath scattering components is supposed to 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 same the LOS condition with high probability. To capture this spatial LOS correlation, we use an exponential correlation model with a correlation distance which depends on the size of obstacles.

MmWave channels differ from traditional sub-6GHz channels, thus requiring new design principles for cooperative communication and system architecture. First, large pathloss and penetration loss on mmWave bands mitigate interference significantly. Second, thanks to sparsity in 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 communication. Third, directional mmWave transmissions provide a new degree of freedom for link scheduling. Last, avoiding blocking is important for the mmWave network design. D2D relaying can increase E2E LOS probability, making it a powerful method for blocking-avoidance in mmWave networks.

III. Hierarchical Control Framework for Multi-connectivity and D2D Relaying

Scalability is a key feature for an operational complex network. For the integrated mmWave/sub-6GHz 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 multi-hop wireless network. Due to the complicated interference situation, traditional multi-hop 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 era, a single-hop paradigm with extreme network densification is challenging in terms of CAPEX/OPEX. A multi-hop paradigm with mmWave relaying is a feasible way to provide high-throughput services with consistent user experience. In general, the complexity of network control increases as the number of hops increases. A tradeoff between the performance and control overhead has to be considered. Two-hop relaying in integrated mmWave/sub-6GHz networks is a favorable solution in the sense of tractable relay management and significant decrease in CAPEX/OPEX.

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 complicated than in a single-hop cellular network, especially for cell-edge UEs. The direct downlink is characterized by two path losses, one for sub-6GHz, one for mmWaves. Since sub-6GHz pathloss is more stable, cell-association should be based on sub-6GHz pathloss 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 interference problems. Multi-user resource allocation is also challenging due to heterogeneity in the resources and links to be scheduled. We consider a scalable hierarchical control framework to address the abovementioned challenges. The network control is based on network state information including traffic loads, link qualities, and interference interactions. In a large-scale network, it is difficult for a centralized controller to access all network state information and make control decisions timely, 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. Fig. 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:

1) In downlink, the first hop of data transmissions from BS to relay always uses mmWave resources while the second hop can use mmWave or sub-6GHz resources.
2) A limited set of relay candidates, typically with LOS to the BS, is selected by the BSs.
3) The destination UEs select a small set of potential relays from the relay candidates and report this set to the BSs.
4) The potential relays are communicated to the BS, and the BS makes the decision of relay selection and allocates resources for each destination UE.
5) Interference management for relaying is performed via limiting the set of potential relays by the BS controller, and by distributed interference coordination locally in the D2D network.
6) The central coordinator sets the parameters used by the lower level entities.

The central coordinator collects global network state information reported by local BS controllers. Information collected from BSs includes: (a) the number of active UEs and their traffic load; (b) the number of active cell-edge UEs and their traffic load; (c) 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: (a) maintaining the set of candidate relays, allocating ID codes to them; (b) collecting channel measurements for BS-to-relay, relay-to-UE and BS-to-UE links; (c) performing relay and beam selection; (d) resource allocation for UEs and relays using the scheduling metric defined by central coordinator; (e) ICIC by dividing resources between cell-center UEs, cell-edge UEs and relays.

Low-level control is distributed in D2D network of UEs and relays. Neighbor discovery is performed, where UEs find D2D neighbors periodically to setup links and measure interference. Downlink and D2D channel quality and interference are measured on both sub-6GHz 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, see Section V.

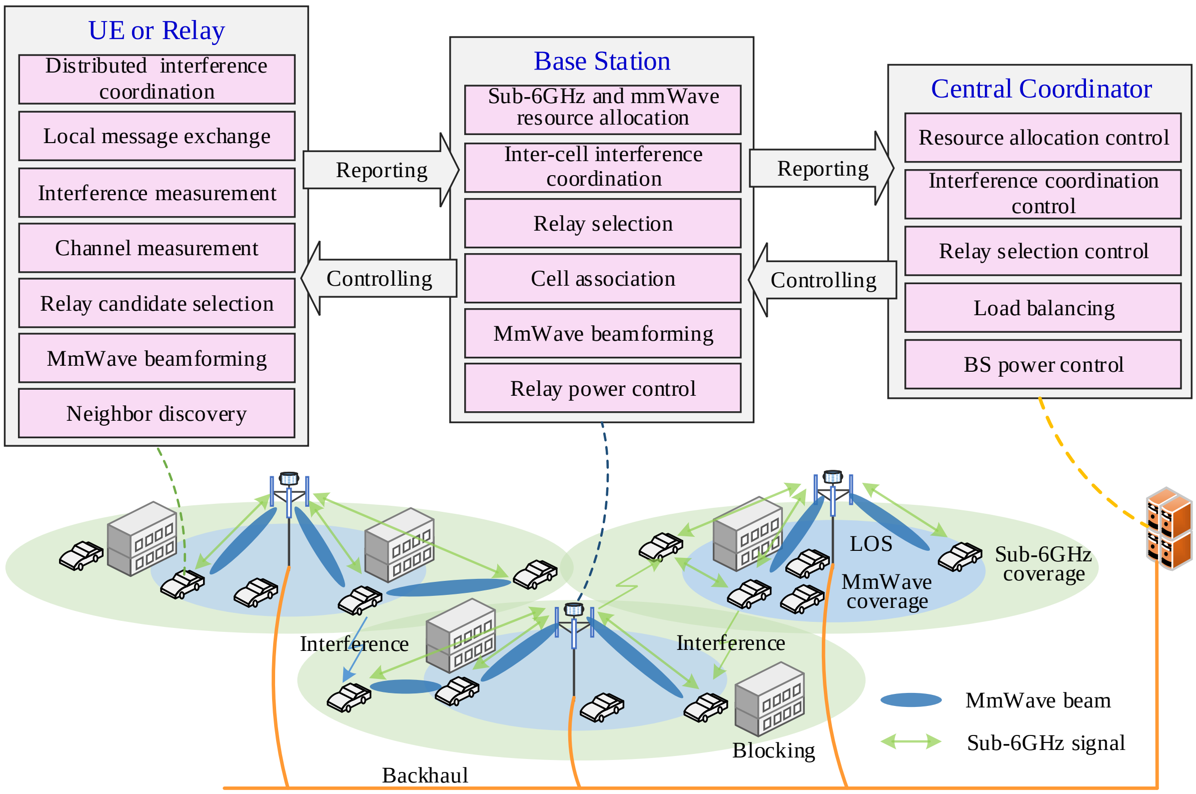


Figure 2. A hierarchical control framework for relaying-enabled integrated mmWave/sub-6GHz networks.

The time scales 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 meters and the UE move at a speed of 30 km/h, the LOS condition may change once per second. The abovementioned 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 detailed changes of the network, the high-level central coordinator is responsible to deal with the average changes of network on time scale of seconds.

IV. Scalable Relay & Beam Discovery and Channel Measurement

In the relaying-enabled network, a high number of measurements have to be performed for interference coordination, relay and beam selection. The amount of measurements is proportional to the number of used beams and size of 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 and UE in an area has a unique TX/RX pattern, and transmits a beacon signal periodically. UEs will try to decode the beacons sent by the neighbors and estimate the link quality and interference power. The beacon signal will encode the information such as node ID, beam ID, interference avoidance requests etc. 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-6GHz discovery signals using omnidirectional broadcasts, and directional mmWave discovery signals using a set of beams.
2) Both active UEs and idle UEs conduct downlink channel measurements on sub-6GHz and mmWave bands, and associate to the best BS on sub-6GHz. The best mmWave TX-RX beam pairs are found for the selected BS.
3) Idle UEs report to the serving BS if the downlink channel quality using optimal beam pairs is larger than a threshold (determined by the central coordinator), informing that it may act as a relay.
4) BS updates and informs the candidate set. Each relay in the set gets an ID code.
5) Candidate relays transmit mmWave beams and sub-6GHz discovery signals for the UEs to perform relay and beam discovery, and D2D channel quality measurements. Relay and beam IDs are embedded to 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-6GHz 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, perform joint mmWave/sub-6GHz resource allocation and the beam assignment for direct, BS-to-relay and D2D links.

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

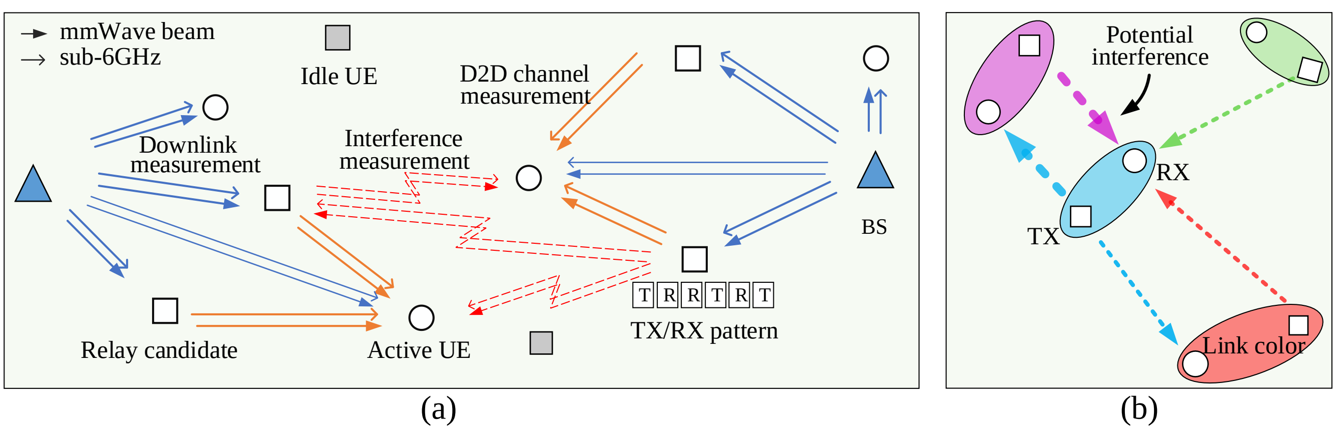


Figure 3. (a) A discovery/measurement framework for the integrated mmWave/sub-6GHz networks with D2D relaying; (b) Local interference graph constructed by interference measurement. Each Relay-to-UE link uses a specific fraction of the D2D resources, indicated by a color. Here the blue and the purple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

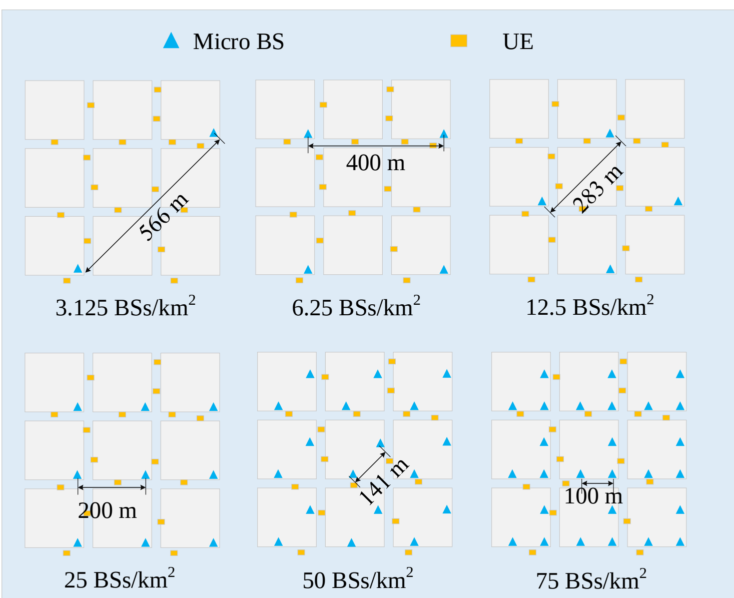
V. Graph-based Methods for Relay Selection, Resource Allocation and Interference Coordination

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 graph coloring method for interference coordination.

1) **Definition of Neighbor Links**: We define two links to be neighbors if the interference from one link to another is larger than a threshold, as compared to the wanted signal power in the other link. Neighboring links using the same radio resource leads to a conflict. When the links are dense in space, usually we cannot solve all conflicts, but the strongest interference can usually be avoided. Fig. 3b shows a local interference graph for one D2D relaying link.
2) **Resource Colors**: Resources reserved for D2D communication are partitioned to fractions, called colors. One D2D link uses one such fraction for communication. For both sub-6GHz and mmWave resources, frequency division multiple access can be used, and resources may be partitioned in both 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.
3) **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.
4) **Resource Allocation:** Both sub-6GHz and mmWave resources may be allocated to a link. In principle, UEs or relays with good mmWave channels would not use sub-6GHz resources. The scarce sub-6GHz resources are allocated to those cell-edge UEs which cannot find a proper relay, or to D2D relaying transmissions. Two methods may be used for allocating resources to relay-to-UE transmissions.
   a. **Random Coloring (RC)**: The resources used for D2D relaying transmissions may be chosen without interference information. Each relay uses a randomly selected fraction of the resources.
   b. **Distributed Interference Coordination (DIC)**: Interference avoidance requests may be used to coordinate interference. The UEs which 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 in Section IV. 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 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 which optimizes a local objective. This distributed interference avoidance is fast as it requires only lightweight message exchange and can be performed locally in one iteration.

VI. Performance Evaluation

We evaluate the performance of mmWave/sub-6GHz 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. The density of destination UEs is one per 50 m on the street and density of idle UEs is six per 50 m. As the ISD decreases, the number of destination UEs associated to each cell will decrease. No beamforming is used for sub-6GHz 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 the angles of multi-path components. Cell-edge UEs can use either sub-6GHz or mmWave relaying depending on the 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-6GHz and mmWave bands based on the 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 & 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.



(a)

Manhattan grid in 1200 m × 1200 m		
Carrier frequency	mmWave	28 GHz
	sub-6GHz	5.9 GHz
Bandwidth	mmWave	500 MHz
	sub-6GHz	40 MHz
Pathloss model	mmWave LOS	$61.4 + 20 \times \log_{10}(d)$ [3]
	mmWave NLOS	$72.0 + 30 \times \log_{10}(d)$ [3]
	sub-6GHz	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-6GHz	BS: 30 dBm UE: 24 dBm
LOS correlation distance		10 m
MmWave antenna array		BS: 8×8 UPA UE: 8×1 UCA
Sub-6GHz 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 Manhattan grid; (b) Simulation parameters.

In Fig. 5 we compare the performance in an integrated mmWave/sub-6GHz deployment to 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% users can achieve throughput above 100

Mbps, while 65% have throughput below 10 Mbps. Multi-connectivity in the integrated deployment can improve both cell-edge and mean performance, as reliable sub-6GHz 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% users above 100 Mbps for integrated deployment and 60% for standalone mmWave. Multi-connectivity combined with RC-relaying in the integrated deployment achieves 170 Mbps mean throughput, as compared to 140 Mbps 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 Mbps for the integrated deployment. For ISD=200 m in Fig. 5b, user experience consistence is improved. About 70% of users now can find a good BS in the mmWave carrier, while the remaining 30% can benefit from multi-connectivity and relaying.

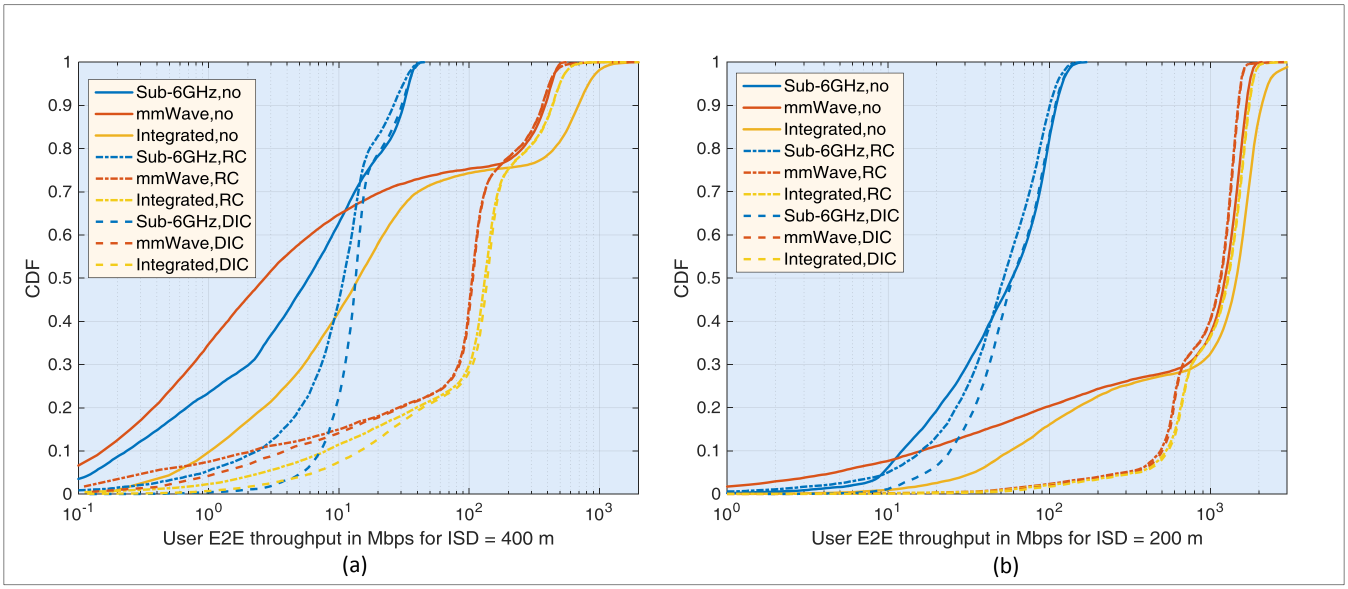


Figure 5. (a) CDF of user E2E throughput in standalone sub-6GHz, standalone mmWave and the proposed integrated mmWave/sub-6GHz (Integrated) deployments with ISD=400 m, for no relaying, relaying with random coloring (RC-relaying), and relaying with distributed interference coordination (DIC-relaying); (b) CDF of user throughput in sub-6GHz, mmWave and integrated deployments with ISD=200 m, for no relaying, RC-relaying and DIC-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% of UEs can achieve throughput above 500 Mbps without relaying, vs. 97% with RC-relaying. For ISD=141 m, 87% vs. 95%, and for ISD=200 m, 72% vs. 92% 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%, for ISD=400 m, 8% vs. 5%, and for ISD=566 m, 2% vs. 0% can reach 500 Mbps. With larger ISD, progressively a 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-6GHz 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 almost have the same performance. For the two smallest ISDs, RC and DIC results are virtually overlapping. Interference conflicts occur mainly in sub-6GHz resources while there is less interference in the mmWave carrier. Due to directivity, interference spreads less in mmWave than in sub-6GHz. In denser networks, most of the D2D links can use mmWave resources. Accordingly, there is a less need for interference coordination between D2D links, and less gain if it is done.

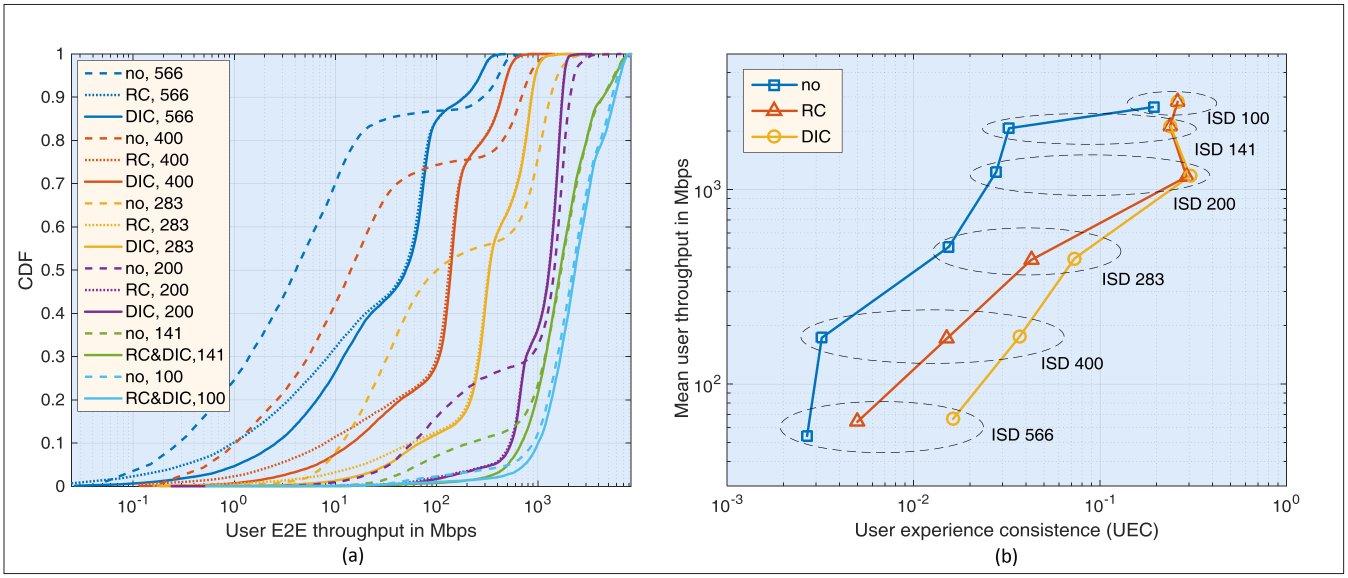


Figure 6. (a) CDF of user E2E throughput in the integrated mmWave/sub-6GHz deployment for six ISD alternatives; (b) 2D plot of UEC vs mean throughput in the integrated mmWave/Sub-6GHz deployment for six ISD alternatives, using a log-log scale.

To characterize cell edge performance, we define a User Experience Consistence (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-6GHz 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 2-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 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 BS/km^2) using relaying can achieve nearly the same performance in the throughput-UEC plane as one with ISD 100 m (75 BS/km^2) and without relaying.

VII. Conclusion

We have considered two-hop downlink D2D relaying in an integrated mmWave/sub-6GHz network as a method to avoid blocking and extend coverage for mmWave communication. Relaying, combined with coordinated resource allocation over the two carriers, improves the data rates experienced at 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-6GHz 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 micro-cell 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-6GHz 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-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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