Coordination context-based spectrum sharing for 5G millimeter-wave networks
- Invited Paper -

Gen Li, Tim Irnich and Cong Shi

***Abstract*—Spectrum sharing is particularly promising for 5G-oriented millimeter-wave (MMW) networks, since MMW network deployments are predominantly expected to be only partially overlapping or adjacent islands, and it would not make sense to assign a dedicated sub-band to each operator in this case. However, inter-network interference may degrade the performance of both networks. Therefore coordination is needed to further improve the network performance. In this paper, a link-specific coordination context (CC) concept is proposed. The CC here for one link represents a constraint that needs to be considered by the scheduler in each AN in a sense that certain transmissions are only scheduled on "allowed" radio resources. To determine CC for each link that suffer non-negligible interference from other networks, the coordination procedure and algorithm is designed in both centralized and distributed structure in this paper. Finally, the performance is evaluated for spectrum sharing of two networks in corridor scenario with realistic ray-tracing propagation channel and steering directional horn antenna models in 60GHz. The results show that high gain beamforming enables more aggressive resource reuse and CC scheme can bring coordination gain over both blind full re-use (i.e. without coordination) and fixed orthogonal re-use (no sharing).**

***Index Terms*— Spectrum sharing, millimeter-wave (MMW) systems, coordination context (CC).**

I. INTRODUCTION

MOBILE broadband will continue to drive the demands for higher overall traffic capacity and higher achievable end-user data rates in the wireless access network. Several scenarios in the future will require data rates of up to 10 Gbps in local areas [1], [2].

These demands for very high system capacity and very high end-user date rates can be met by networks with distances between access nodes ranging from a few meters in indoor deployments up to roughly 50 m in outdoor deployments, i.e. with an infra-structure density considerably higher than the most dense networks of today [3]. The wide transmission bandwidths needed to provide data rates up to 10 Gbps and above can likely only be obtained from spectrum allocations in the millimeter-wave band. High-gain beamforming, typically realized with array antennas, can be used to mitigate the increased pathloss at higher frequencies. We refer to such networks as MMW networks in the following.

A. Why spectrum sharing in MMW networks?

MMW networks have a number of properties that, generally speaking, make operation under shared spectrum promising [3].

Due to the small antenna size at high frequencies MMW networks will heavily rely on high-gain beamforming, which will enable significantly higher resource reuse and alleviate the interference situation between multiple networks.

It is expected that these networks will predominantly be deployed in the form of "high-capacity coverage islands" in areas where very high traffic demand is expected or very high connection speed is required. This suggests that an area will normally only be covered by one network rather than having multiple parallel networks deployed by different operators and covering the same area. Hence, inter-network interference will predominantly occur between partially overlapping, adjacent or neighboring (i.e. with some distance in-between) networks.

In such a situation it is obviously preferable to avoid fragmentation of the available bandwidth into one

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G. Li and C. Shi are with Ericsson Research, Ericsson (China) Communications Co. Ltd, 100102, Beijing, China (e-mail: gen.li@ericsson.com, cong.shi@ericsson.com).

T. Irnich is with Ericsson Research, Ericsson GmbH, 521 34 Herzogenrath, Germany (e-mail: tim.irnich@ericsson.com).

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exclusive sub-band per network, since large amounts of spectrum would remain unused at times when networks are not simultaneously fully loaded, and peak data rates would be limited to a fraction of what could theoretically be achieved. It would instead be preferable that each MMW network can access the full available frequency bandwidth in order to maximize spectrum utilization and supported peak data rate.

B. *Why not just do it like Wi-Fi?*

In this case it would however be necessary to design technology so that residual interference in border areas between two independent networks can be handled in an efficient way. Wireless LAN systems like IEEE 802.11 natively support such a scenario, but the principle of contention-based access to radio resources used there has the fundamental difficulty that overhead grows over-proportionally when system load increases. In combination with beamforming this problem would be even more pronounced due to an increase of occurrence of the hidden node problem.

One key advantage of contention-based access is that the scheme is purely based on observation of the channel, i.e.no explicit exchange of information between systems is required. This is obviously a great advantage in unlicensed bands where different technologies have to share the spectrum and operators of other radio systems are usually unknown, and this advantage outweighs the disadvantage of non-graceful degradation at high load for the case of unlicensed spectrum.

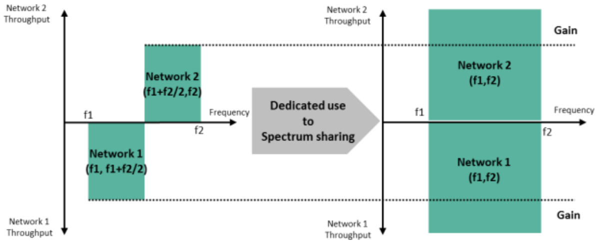


Fig. 1 Illustration of requirement for spectrum sharing.

In the case of licensed shared spectrum, however, sharing schemes that rely on explicit exchange of information between the participants in principle have the potential to overcome the problem of non-graceful degradation at increasing load [1], [2]. Their drawback is that they only work if all participating systems implement the required functionality. This makes such schemes not generally applicable in unlicensed bands. In licensed shared bands, however, where it can be expected that compliance with certain specifications can be either enforced or agreed between licensees, it is very well conceivable that spectrum sharing can successfully be implemented through explicit exchange of information between networks, i.e. coordination. This way, a stable and predictable system behavior also at high load could be achieved. As shown in Fig. 1, A key requirement to such a scheme would be that each participating system achieves the same performance as in a dedicated licensed scheme where each network would have its own sub-band.

C. *Related work and contribution of this paper*

Coordinated intra-system (inter-cell) spectrum re-use is already widely studied in current cellular networks. For example, the Almost Blank Subframe (ABS) concept has been intensively studied to reduce interference between LTE Macro and Pico cells in heterogeneous network scenarios [5]. Similarly, the Dynamic Point Blanking (DPB) concept has been proposed to improve the performance of Coordinated Multi-Point (CoMP) transmission and reception [6].

However, coordination for inter-network spectrum sharing differs from intra-network coordination in an number of aspects.

Inter-network interference may be stronger than intra-network interference since the mobile terminal belonging to another network is closer than the transmitter we are connected to. The potential gain is therefore larger.

Furthermore, the coordination objective is different. The objective for inter-network coordination is mainly fairness and equitable access to spectrum resources while for intra-network coordination the goal is usually to improve the overall network capacity. This means that it is perfectly acceptable that one of the coordinating entities makes a significant sacrifice for the benefit of overall sum utility.

Finally, inter-network coordination should be slower than intra-network in time scale, in order to obtain a basis for network internal radio resource management that can be valid for a relatively long time.

This paper proposes spectrum sharing solutions for 5G MMW networks in high frequency band (e.g. over 30GHz). The objectives of this paper is to (i) identify the inter-network spectrum sharing scenario for MMW networks and (ii) design coordination scheme taking into account special properties and features of MMW networks and (iii) simulate the proposed scheme using realistic indoor propagation channel & antenna models for MMW networks and quantify the performance gains over a non-coordinated baseline case.

II. SPECTRUM SHARING SCENARIO BETWEEN DIFFERENT MMW NETWORKS

Due to high frequency band and small coverage, MMW networks are predominantly expected to be deployed in the form of "coverage islands" serving high traffic density areas (e.g. an office building, a shopping mall, etc.). Different MMW networks may be running in

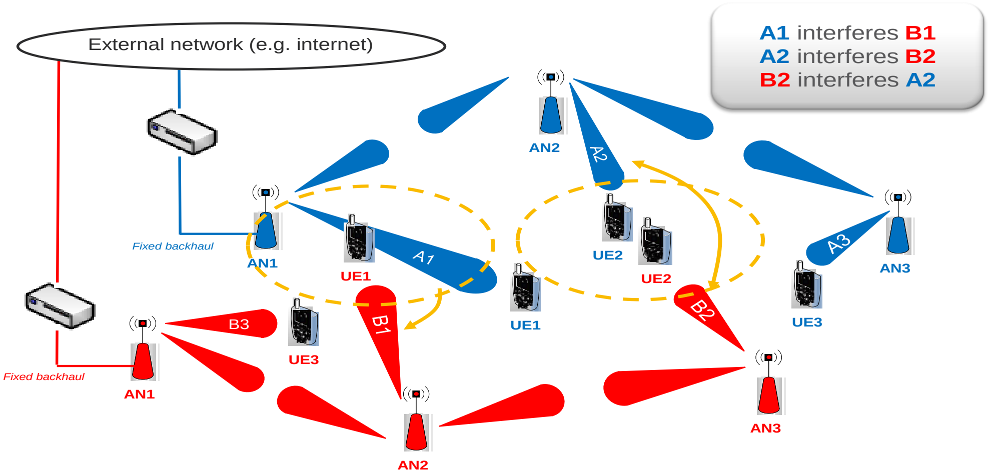


Fig. 2 Illustration of two MMW networks in an overlapping area and the resulting interference scenario. Interference occurs between specific link pairs and may be uni-directional.

the same or overlapping area.

For example, there are two MMW networks (blue for MMW network A and red for MMW network B) as shown in Fig. 2. They are located in the same area and operate on the same channel. Hence they will cause interference to each other.

We define the *acceptable interference threshold* (AIT) as the interference level that would not trigger coordination if actual interference stays below. One example for how to define the AIT is that interference up to the AIT does not impact the current selection of modulation and coding at a receiver.

Other scenario assumptions are that we have a scheduled frame-based system that partitions radio resource for multiple access in the time and/or frequency domain, that nodes within one network are synchronized in time and frequency, and that there is at least time synchronization across networks.

The key problem to be solved in this paper is how to coordinate scheduling of interfering links between different MMW networks so that interfering transmissions do not end up on the same radio resources and with that the non-acceptable inter-network interference is alleviated to achieve better spectrum efficiency.

Two straight forward solutions that we will use as reference cases are introduced as follows:

- *Orthogonally resource (OR) use:* Similar to traditional dedicated use of spectrum among different operators in today's mobile networks, the whole resource is divided into orthogonal parts and each MMW network use only one part;
- *Blind full resource (BFR) reuse:* All the MMW networks use the whole resource without any coordination between them.

It is easily seen that the first solution may result in low spectrum efficiency if the interference between different systems is not severe. For the second one, the interference between different systems cannot be avoided so that some links may have bad performance or seamless coverage cannot be guaranteed. Hence, a coordination solution is proposed in the following to overcome the weaknesses of these two reference cases.

III. COORDINATION CONTEXT-BASED SCHEME

The objective is a solution that coordinates radio resource usage on a "per link" basis, i.e. only transmission links that actually create non-negligible interference (beyond a given threshold) to particular other links should be subject to coordination. Here, coordination means that transmissions of an inter-network interference link pair (one link in one MMW network and one in the other) are subject to scheduling constraints so that they cannot be scheduled on the same (time/frequency) radio resources.

The two interfering networks negotiate an agreement on such a resource partitioning and record it in the form of a Coordination Context (CC) which is stored in a Coordination Context Database (CCDB) in each network. The CC thus represents a constraint that needs to be considered by the scheduler in each network.

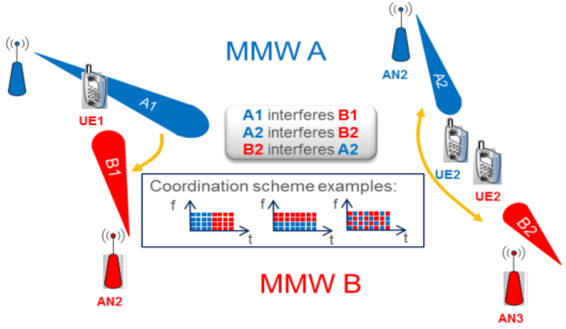


Fig. 3 Illustration of coordination context concept.

For example as shown in Fig. 3, A1 and B1 is an interfering link pair between different MMW networks. As a result of coordination, they will be coordinated to that the blue resources are reserved for A1 and the red resources for B1. In general, the resource division for one interference link pair can be in time, frequency or both.

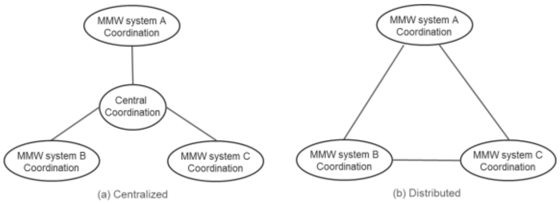


Fig. 4 Illustration of centralized and distributed coordination.

Such coordination scheme can be implemented in a distributed and in a centralized manner.

A. *Centralized implementation*

The determination of coordination context can be implemented in a centralized way, see Fig. 4 (a), i.e. a central coordination functionality (CCF) is connected to multiple MMW networks, and each network has a system coordination functionalities to act as a counterpart for the central entity. System coordination functionality (SCF) here is specific to one network and has logical connections to each access nodes (AN) within the network. SCF is responsible for relaying the information on potential scheduling constraints from CCF to AN, e.g. interference information and CC results. The key idea of centralized implementation is that CCF collects the full interference information from different MMW networks and makes final decisions on the links which needs CC to avoid interference above the acceptable interference threshold. The following procedures would be needed in the case of centralized implementation:

Step 1 – Inter-network interference detection is operated in each AN through an interference measurement process. In order to facilitate the CC concept, the interference should be identified in terms of link level, i.e. which link is interfered by which link in which MMW network. The links operated by a particular AN, are either aggressor (they cause interference to some link in another network), victim (the received interference from a link in another network) or interference-free links. By interference measurement support mentioned above, each AN can however only identify the victim links under itself and the corresponding aggressor links from other MMW networks.

Step 2 – Interference information transfer: The measured interference information will be transferred to CCF from each SCF and form the base of the CC decision. The interference information will mainly include the inter-network interference link pair, where each link will be represented as a link ID (e.g. transmitter ID + receiver ID). Each AN will report the measured inter-network interference link pair to its connected SCF, which will aggregate all the received information and send them to the CCF.

Step 3 – Coordination context decision: Through collecting information from multiple SCFs, CCF will obtain interference information from the involved multiple connected UDNs, e.g. A1->B2, A1<-B4, A1->C3, A5->C2, B4->C2, B3<-C3 where each arrow points to the victim link. Based on this information, CCF can establish an interference graph by considering link and interference relationship as vertex and edge respectively. In this way, the stored information can for example form interference graph as shown in Fig. 5 (a).

In order to avoid severe interference between different MMW networks, the interference link pair (e.g. A1->B2) should be scheduled to different (i.e. orthogonal) radio resources. If we use different colors to represent orthogonal resource, the CC determination problem can become the following graph coloring problem:

Graph coloring problem: Given a graph *G(V,E)*, where *V* is the set of vertices and *E* is the set of edges, find minimum *k*, and mapping *r*: *V* *{1,…,k}* such that $r(i) \neq r(j)$ for each edge $(i, j) \in E$.

Graph coloring is perhaps one of the most notorious of the NP-complete problems. Numerous algorithms have been developed for approximate coloring [7]. The simple greedy algorithm starts with some permutation of the vertices and as each vertex is considered in turn, it is assigned the minimum color that does not cause a conflict. For example, following the permutation (A1, B2, B4, C3, B3, C2, A5), Fig. 5 (b) gives the coloring solution for the graph example in Fig. 5 (a). Here the output minimum number of colors needed is 2 and the color mapping results as Fig. 5 (b) shows.

For each possible color rank *k*, the resource pool should be divided into *k* orthogonal parts for CC translations (e.g. left side of Fig. 6). Hence, CC database can be established as shown in right side of Fig. 6.

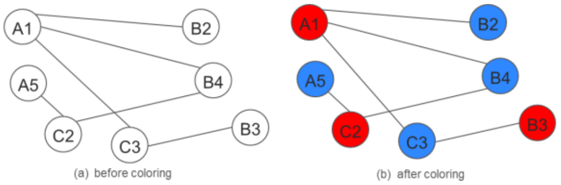


Fig. 5 Illustration of interference graph example (circle means link).

Link Pair	CC for first Link	CC for latter link
A1 -> B2	REG-blue-rank2	REG-red-rank2
A1<-B4	REG-blue-rank2	REG-red-rank2
A1->C3	REG-blue-rank2	REG-red-rank2
A5->C2	REG-red-rank2	REG-blue-rank2
B4->C2	REG-red-rank2	REG-blue-rank2
B3<-C3	REG-blue-rank2	REG-red-rank2

Fig. 6 CC database example (REG: resource element group).

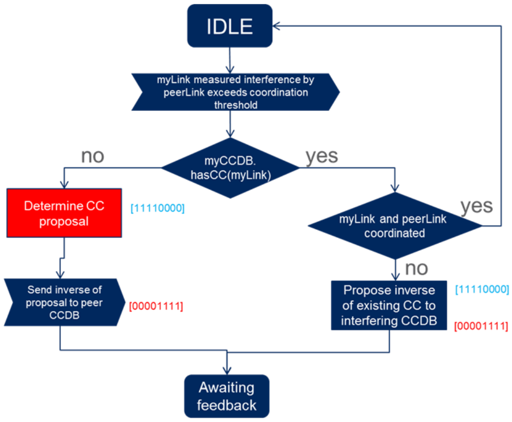


Fig. 7 Process for CC establishment on the victim side. The red box “determine CC proposal” is a placeholder for a possibly more complex procedure which can be implemented in many different ways.

Step 4 – CC-based scheduling: Once CC is determined, CCF needs to signal the CC results to each AN as scheduling basis. After it receives CC report, AN will schedule the links included in CC report in allowed resource elements. For the link without CC, it can be scheduled in any place of the whole resource grid.

B. *Distributed implementation*

Centralized solutions are expected to be useful for scenarios where a centralized entity is already present for other reasons. This may not be always be the case. In these cases a distributed approach may be more preferable, as shown in Fig. 7.

Upon detecting interference that exceeds the coordination threshold, the victim network sends a dedicated initial CC proposal message sent to the interfering network and then waits for feedback (confirmation or CC counter-proposal) from the interfering network.

The interference is measured by the victim node, and compared with a predefined threshold. If the value of the interference exceeds the predefined threshold, then the coordination procedure is initiated.

The CC proposal depends on whether the considered link is already subject to coordination or not (see Fig. 7). If the link is not yet coordinated, a CC proposal (which e.g. assigns the first 50% of the resources to the victim network and the other 50% to the interfering network) is determined and sent to the peer network. If the link is already coordinated, the inverse of the already existing CC is proposed to the interfering network in order to avoid additional constraints on radio resource usage on the victim side.

It is also possible that the CC proposal when the link is not yet coordinated is based on a predicted own resource demand and may claim more or less than 50% of the resources. When receiving a CC proposal, the network receiving the proposal first checks if it already has a CC for the considered link, see Fig. 8. If so, it merges the newly proposed CC with the already existing CC (for example by using a logical AND concatenation) and then checks if it agrees with the resulting received proposal. One possible criterion to decide this is the remaining amount of radio resources according to the proposal.

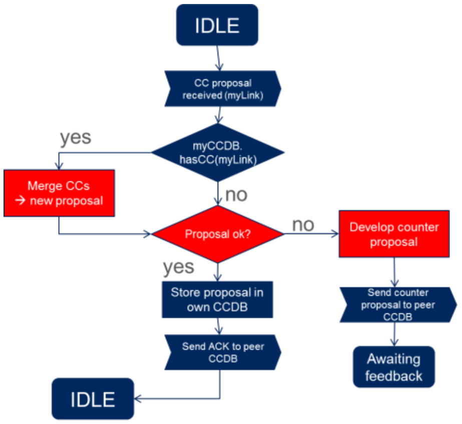


Fig.8 Process for receiving and responding to a CC proposal. The red blocks are placeholders for possibly more complex procedures which can be implemented in many different ways.

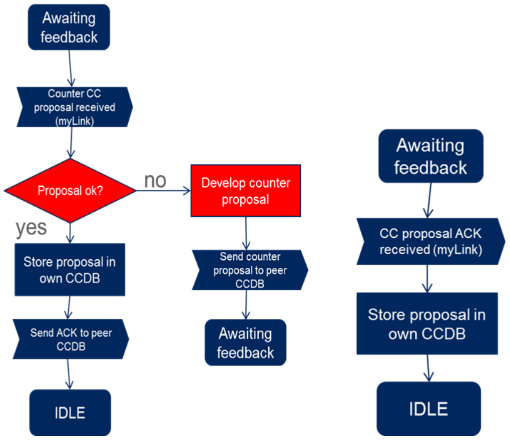


Fig.9 Process while awaiting feedback (a) left side: for receiving a counter-proposal; (b) right side: for receiving a confirmation on a previously sent CC proposal

If the proposal is acceptable, the CC proposal is stored in the CC database (CCDB) and an acknowledgement message is sent to the victim network. If not, the interfering network sends a counter-proposal to the victim network. One possible way to develop a counter-proposal is to claim the same amount of resources the original proposal contains, but to select other resources as available so that the overall amount of resources keeps the same.

This counter-proposal is then either accepted or answered with another counter-proposal by the victim network; see Fig. 9 (a). This procedure is potentially (i.e. this is an option) limited to a finite number of times before, if no CC has been agreed so far, the process is aborted and the two networks continue operation in an uncoordinated way. If a confirmation message is received while waiting for feedback on a previously sent CC proposal, the network stores the CC proposal in its own CCDB and returns to IDLE state (the coordination process is completed), see Fig. 9 (b).

IV. PERFORMANCE EVALUATION

The performance for inter-network coordination is evaluated in an indoor environment. Specifically, a floor plane of dimensions 25 m by 30 m by 3 m, with 6 rooms connected by a middle corridor as shown in Fig. 10, is used. Two different MMW networks are deployed within this scenario. As one baseline scenario, there are one AN and 8 UEs deployed for each network as shown in Fig. 10. ANs are in fixed symmetric positions on the ceiling and UEs are uniformly distributed in different areas (one for left side rooms & corridor and the other for right side rooms & corridor). Note that ANs are all placed at the ceiling (3m) and UEs are assumed to be 1.5m above the ground.

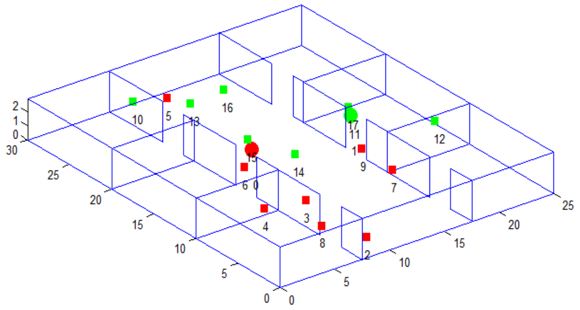


Fig.10 Office corridor floor plane, distance scales are in meters.

A. Simulation Settings

The main system parameters for performance evaluation are given in the following table:

Table 1 Simulation Parameters

Number of Access Nodes	2
Channel Model	Ray-Tracing (up to 2 reflections with reflection loss 5.6 dB) combined with antenna gain for each ray
Carrier Frequency	60 GHz
Multiplexing Scheme	TDMA (DL:UL=1:1)
Frame length	1 ms
Subframe Period	25 µs
Maximum Tx Power	AN: 15 dBm, UE: 15 dBm
Thermal Noise Level	-174 dBm/Hz
Noise Figure	9 dB
Traffic	Full buffer
Coordination threshold	88 dB

A ray-tracing channel model [8] is used to simulate the quasi-optical propagation characteristics of radio signals in the millimeter-wave (MMW) bands in an indoor environment. It is used to generate LOS and reflection rays between any two nodes.

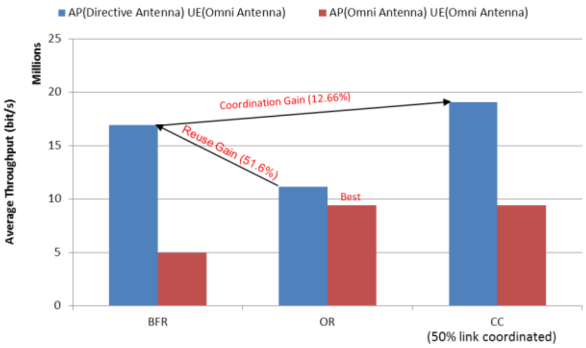


Fig.11 Downlink throughput for different schemes with different antenna configurations at AN.

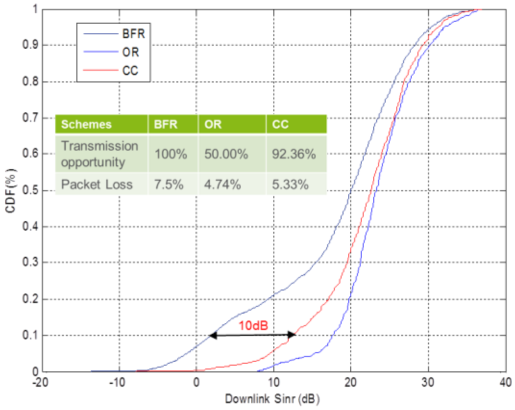
There are two kinds of antennas used in our evaluation, i.e. isotropic antenna and horn antenna. Horn antenna is used to represent the high gain beamforming feature of MMW networks in a simple way and the direction of main beam is assumed to be steerable according to the maximum ray direction.

Besides the above mentioned configuration, other system parameters are given in the following table:

B. Simulation Results

Fig. 11 gives the downlink throughput performance results for orthogonal resource (OR) use, blind fully resource (BFR) reuse scheme as introduced in section II and the proposed coordination context (CC) scheme. First, it can be seen that traditional OR is best when ANs are configured with omni antenna, since the inter-network interference is very large in this case. Second, high gain beamforming feature improves the interference situation a lot and brings large throughput gain (beamforming gain) by comparing directive and omni antenna in any spectrum use case. Third, in directive antenna configuration, our inter-network coordinated spectrum sharing concept can obtain coordination gain compared to BFR case and of course it also has the same reuse gain compared to OR case. The main conclusion is that high gain beamforming and coordination makes inter -network spectrum sharing possible and reasonable.

Figure 12 shows the SINR performance of different schemes for the baseline scenario. OR scheme, as expected, has best SINR due to no inter-network interference but 50% of transmission opportunities lost. Compared to BFR, CC scheme greatly improves the SINR performance and packet loss ratio. It can additionally be observed that the largest improvement of SINR can be observed for the low percentiles of the CDF, indicating that coordination is not only helpful for capacity but also for improving cell coverage. Furthermore compared to OR, the transmission opportunity is significantly enhanced. Hence, CC scheme can achieve better tradeoff of signaling quality and transmission opportunity.



Schemes	BFR	OR	CC
Transmission opportunity	100%	50.00%	92.36%
Packet Loss	7.5%	4.74%	5.33%

Fig.12 Downlink SINR CDF for different schemes with directive antenna configuration at AN side.

V. Summary and Conclusions

In this paper, we investigated the feasibility of spectrum sharing for MMW network in indoor environment. Based on the high gain beamforming feature for each link in MMW networks, we proposed a link-specific coordination context concept to avoid the severe interference between different networks. Both centralized and distributed solutions are considered from implementation aspects. Furthermore, the performance is evaluated for spectrum sharing of two MMW networks in office corridor scenario with realistic ray tracing propagation and steering directional horn antenna models in 60 GHz. Blind fully resource reuse scheme and orthogonal resource use scheme are simulated for comparison.

As an overall conclusion from this paper, coordinated spectrum sharing is a viable spectrum use solution for MMW networks. First, the high gain beamforming feature of MMW networks in high frequency band enables more aggressive spectrum reuse than the traditional orthogonal resource use between different networks. Second, the proposed coordination context-based solution can improve the average system throughput compared to traditional schemes, even for full reuse the whole spectrum by multiple different networks belonging to different operators.

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