A Supplementary Document for the Paper: Deep Reinforcement Learning Based Scheduling for NR-U/WiGig Coexistence in Unlicensed mmWave Bands

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I. Introduction

This is a supplementary document for our paper: Deep Reinforcement Learning Based Scheduling for NR-U/WiGig Coexistence in Unlicensed mmWave Bands. In this document, we provide various network topologies for the coexistence of NR-U and WiGig in Section V of our paper. In general, as shown in Fig. 1, we consider an unlicensed mmWave HetNet, in which the NR-U network and the WiGig network share a common wireless channel to transmit data packets. To be specific, M multi-antenna APs and multiple single-antenna STAs are deployed in the WiGig network, and the NR-U network is composed of a multi-antenna gNB and N single-antenna UEs deployed around the WiGig STAs. Furthermore, the gNB in the NR-U network is equipped with K independent panels; and each panel $k \in \mathcal{K} = \{1, 2, \cdots, K\}$ is responsible for serving one specific UE group k containing N_k UEs located in a fixed region without interfering with other panels, wherein $\sum_{k=1}^{K} N_k = N$. In the following, we will introduce the detailed network topologies for the coexistence of NR-U and WiGig in Section V of our paper.

A. Data Rate Evaluation

The network topology corresponding to the coexistence scenario in Section V-B of our paper is presented in Fig. 2, where UEs and STAs are randomly deployed within 20 meters from gNB and corresponding APs, respectively. The gNB in the NR-U network is equipped with four panels which serve 2, 3, 3, and 4 UEs, respectively. Among all the distances from UEs to gNB, the shortest is 5 meters, and the farthest is 20 meters. In the WiGig network, there are 3 WiGig APs each serving 4 STAs, and the distance from each WiGig AP to gNB is 15 meters.

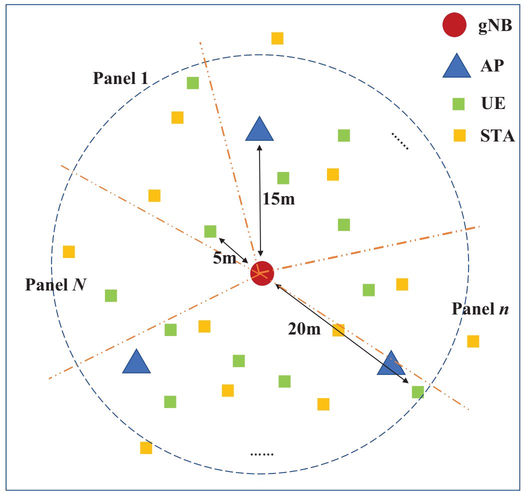


Fig. 1. The general NR-U/WiGig coexistence system.

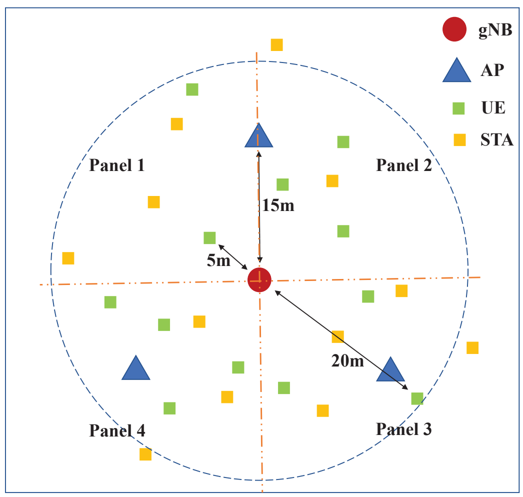


Fig. 2. The network topology for the coexistence scenario in Section V-B of our paper.

B. Robustness to Different Data Rate Requirements

As shown in Fig. 3, in the network topology corresponding to the coexistence scenario in Section V-C1 of our paper, UEs and STAs are randomly deployed within 20 meters from gNB and corresponding APs, respectively. In the NR-U network, the gNB possesses three panels and each panel serves three UEs. Among all the distances from UEs to gNB, the shortest is 5 meters, and the farthest is 20 meters. In the WiGig network, there are 3 WiGig APs each serving 4 STAs, and the distance from each WiGig AP to gNB is 15 meters.

C. Robustness to Different Numbers of UEs

In Section V-C2 of our paper, we evaluate the robustness of various scheduling mechanisms by changing the number of UEs served by each panel. Therefore, there are multiple network topologies for this coexistence scenario,

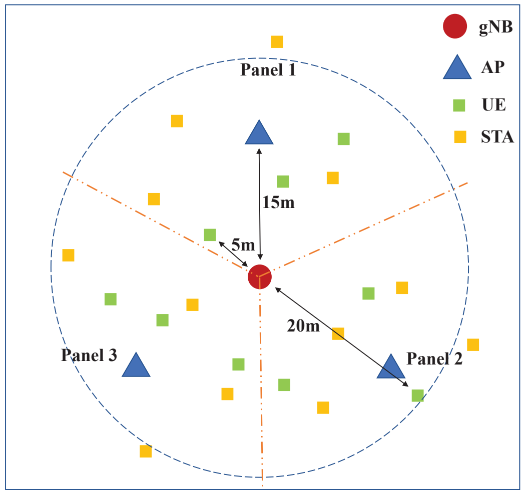
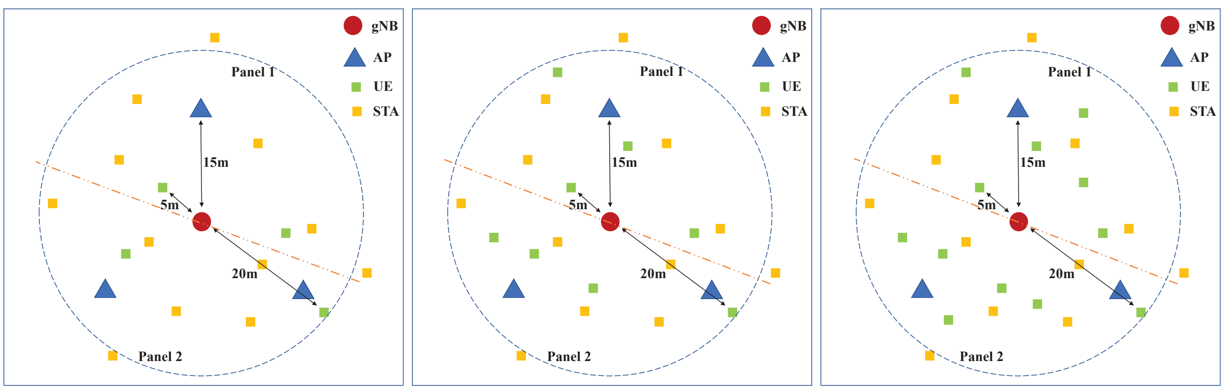


Fig. 3. The network topology for the coexistence scenario in Section V-C1 of our paper.



(a) Each panel serves 2 UEs.

(b) Each panel serves 4 UEs.

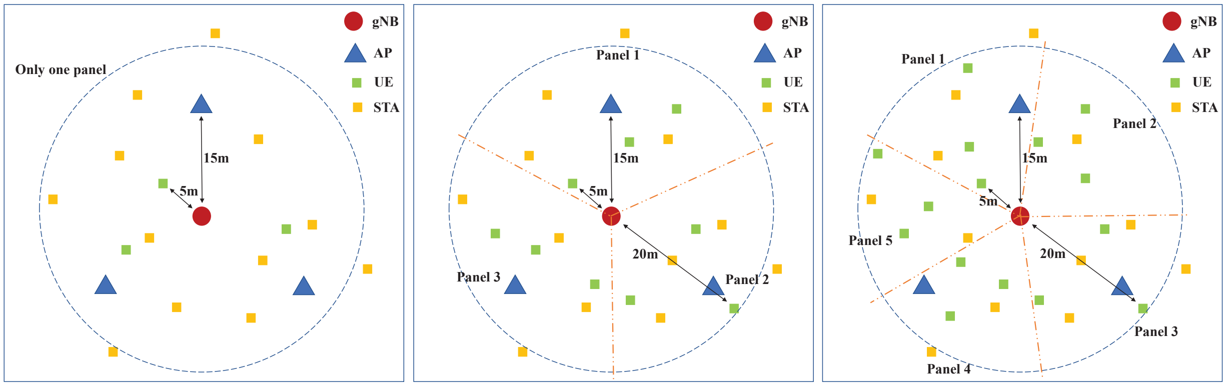
(c) Each panel serves 6 UEs.

Fig. 4. The network topologies for the coexistence scenario in Section V-C2 of our paper.

which are depicted in Fig. 4. In all network topologies, UEs and STAs are randomly deployed within 20 meters from gNB and corresponding APs, respectively. In the WiGig network, there are 3 WiGig APs each serving 4 STAs, and the distance from each WiGig AP to gNB is 15 meters. In the NR-U network, the gNB adopts two panels to serve all UEs, where the number of UEs in each panel is varied from 2 to 6 with a step size of 2. Specifically, Fig. 4a, Fig. 4b, and Fig. 4c show the scenarios where each panel serves 2, 4, and 6 UEs, respectively. Among all the distances from UEs to gNB, the shortest is 5 meters, and the farthest is 20 meters.

D. Complexity Evaluation of DeepDS and DeepCS

In Section V-D of our paper, we evaluate the complexity of DeepDS and DeepCS by changing the number of panels at gNB. Therefore, there are multiple network topologies for this coexistence scenario, which are presented in Fig. 5. In all network topologies, UEs and STAs are randomly deployed within 20 meters from gNB and corresponding APs, respectively. In the WiGig network, there are 3 WiGig APs each serving 4 STAs, and the



(a) The gNB is equipped with 2 panels. (b) The gNB is equipped with 3 panels. (c) The gNB is equipped with 5 panels.

Fig. 5. The network topologies for the coexistence scenario in Section V-D of our paper.

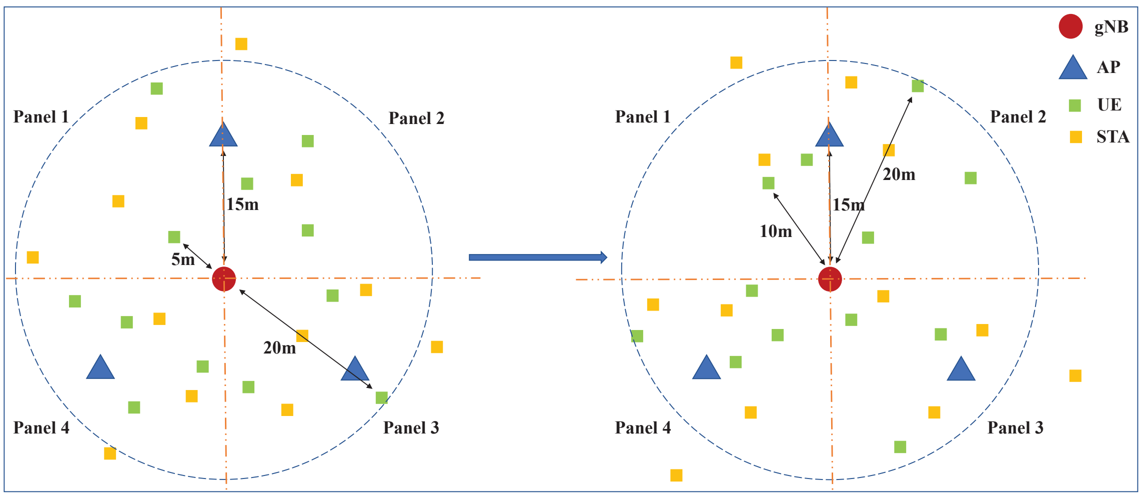
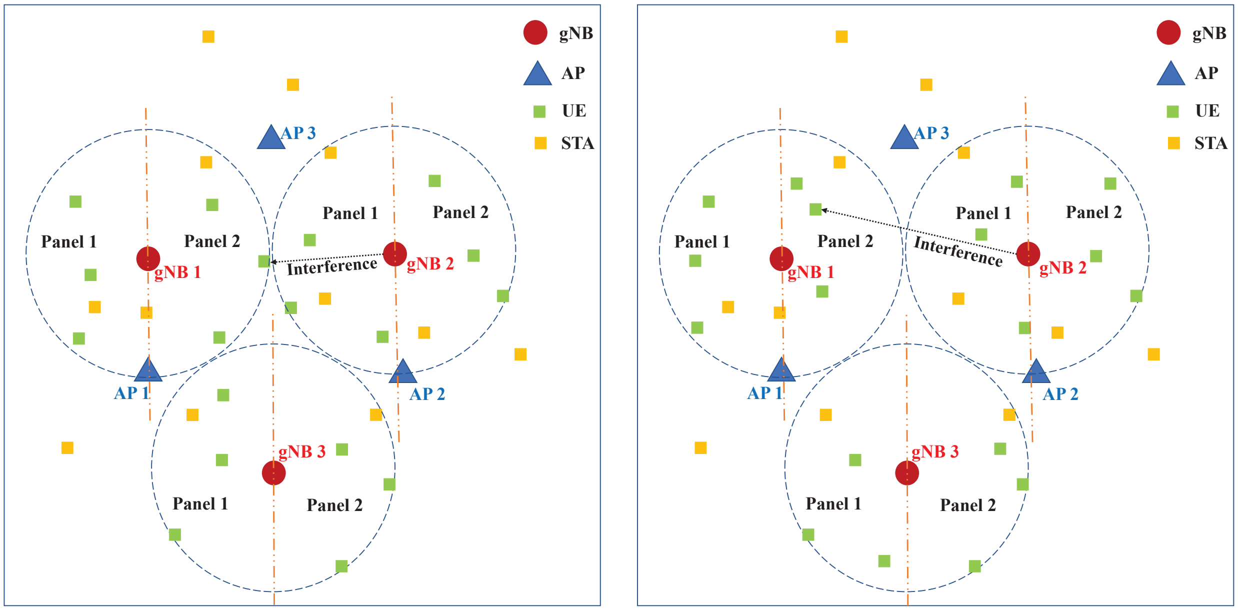


Fig. 6. The network topology for the coexistence scenario in Section V-E of our paper.

distance from each WiGig AP to gNB is 15 meters. In the NR-U network, the gNB is equipped with K panels each serving three UEs, where the value of K from 1 to 5 with a step size of 2. Specifically, Fig. 5a, Fig. 5b, and Fig. 5c show the scenarios where the number of panels are 1, 3, and 5, respectively. Among all the distances from UEs to gNB, the shortest is 5 meters, and the farthest is 20 meters.

E. Adaptiveness to Environmental Changes

In this section, we evaluate the adaptiveness of the proposed algorithms to the environmental change. As provided in Fig. 6, in the network topology corresponding to the coexistence scenario in Section V-E of our paper, UEs and STAs are randomly deployed within 20 meters from gNB and corresponding APs, respectively. The gNB in the NR-U network is equipped with four panels which serve 2, 3, 3, and 4 UEs, respectively. In the WiGig network, there are 3 WiGig APs each serving 4 STAs, and the distance from each WiGig AP to gNB is 15 meters.



(a) Case (i).

(b) Case (ii).

Fig. 7. The network topologies for the coexistence scenario in multi-gNB scenarios.

The detailed distance descriptions between gNB and its UEs are given as follows. In the beginning (i.e., the left figure in Fig. 6), among all the distances from UEs to gNB, the shortest is 5 meters, and the farthest is 20 meters. The data rate requirements of these 12 UEs are randomly initialized from the set $\{0.5, 1, 1.5\}$ Gbps. At the 50000-th time slot, the locations of all UEs and STAs along with their data rate requirements in the system all change, as shown in the right figure in Fig. 6. In this scenario, among all the distances from UEs to gNB, the shortest is 10 meters and the farthest is 20 meters. The data rate requirements of all UEs are re-selected from the set $\{0.5, 1, 1.5\}$ Gbps in random.

F. Performance Evaluation in Multi-gNB Scenarios

Due to the limited page length, we omit this part in our paper. As shown in Fig. 7, in these two network topologies, UEs and STAs are randomly deployed within 20 meters from gNB and corresponding APs, respectively. In the WiGig network, there are 3 WiGig APs each serving 4 STAs. In NR-U systems, there are three NR-U networks each consisting of one gNB and six UEs. In each NR-U network, the gNB possesses two panels and each panel serves three UEs. Furthermore, different gNBs may interfere with each other, as presented in Fig. 7. To be specific, we consider two different network topologies: Case (i) the mutual interference among different gNBs is relatively large due to the proximity of UEs served by different gNBs or the short distances between UEs and gNBs of other NR-U networks; and Case (ii) there is little mutual interference among different gNBs.

We provide the detailed distance descriptions among gNBs, APs, UEs, and STAs as follows.

- Case (i). As shown in Fig. 7a, among all the distances from gNB1 to its UEs, the shortest is 7 meters and the farthest is 15 meters; among all the distances from gNB2 to its UEs, the shortest is 11 meters and the farthest is 15 meters; and among all the distances from gNB3 to its UEs, the shortest is 7 meters and the farthest is 15 meters. The distances from WiGig AP 1 to gNB 1, gNB2, and gNB3 are 20, 35, and 22 meters, respectively; the distances from WiGig AP 2 to gNB 1, gNB2, and gNB3 are 35, 20, and 22 meters, respectively; and the distances from WiGig AP 3 to gNB 1, gNB2, and gNB3 are 22, 22, and 38 meters, respectively.

- Case (ii). As shown in Fig. 7b, among all the distances from gNB1 to its UEs, the shortest is 4 meters and the farthest is 15 meters; among all the distances from gNB2 to its UEs, the shortest is 4 meters and the farthest is 15 meters; and among all the distances from gNB3 to its UEs, the shortest is 7 meters and the farthest is 15 meters. The distances from WiGig AP 1 to gNB 1, gNB2, and gNB3 are 20, 35, and 22 meters, respectively; the distances from WiGig AP 2 to gNB 1, gNB2, and gNB3 are 35, 20, and 22 meters, respectively; and the distances from WiGig AP 3 to gNB 1, gNB2, and gNB3 are 22, 22, and 38 meters, respectively.

The data rate requirements of these 18 UEs are chosen from the set $\{0.5, 1\}$ Gbps in random. TABLE I summarizes the total data rate of NR-U networks, the total data rate of WiGig systems, and the number of satisfied UEs attained by various scheduling schemes.

- Case (i): the mutual interference among different gNBs is relatively large. As can be seen from TABLE I, DRL based algorithms, although obtaining a slightly lower data rate of WiGig compared with dirLBT and omniLBT, significantly improve the data rate of NR-U. Specifically, in terms of the overall data rate of HetNets, (i) DeepDS outperforms dirLBT and omniLBT by 17.6% and 18.7%, respectively; and (ii) DeepCS outperforms dirLBT and omniLBT by 13.3% and 14.3%, respectively. Furthermore, compared with other schemes, DeepDS and DeepCS can satisfy the data rate requirements of more UEs. Nevertheless, we find that DeepDS and DeepCS cannot meet the data rate requirements of all UEs. This is because that different gNBs interfere with each other but there is no any coordination mechanism among them. In this case, cooperative multi-agent DRL will be a more suitable technique to design the efficient scheduling scheme for NR-U, which will be presented in our future work.
- Case (ii): there is little mutual interference among different gNBs. As can be seen from TABLE I, DRL based algorithms, although achieving a slightly lower data rate of WiGig compared with dirLBT and omniLBT, significantly improve the data rate of NR-U. Specifically, in terms of the overall data rate of HetNets, (i) DeepDS outperforms dirLBT and omniLBT by 26.4% and 25.5%, respectively; and (ii) DeepCS outperforms dirLBT and omniLBT by 22.7% and 21.8%, respectively. Furthermore, unlike other algorithms, DeepDS and DeepCS can satisfy the data rate requirements of all UEs. We can also find that in terms of the data rate of NR-U, compared with DRL based algorithms, omniLBT and dirLBT are more sensitive to the magnitude of interference among gNBs. In other words, the gaps between the NR-U data rates achieved by omniLBT and dirLBT in the two cases (i.e., case (i) and case (ii)) are larger than that of DRL based algorithms. This is because that the gNB uses omniLBT or dirLBT will start transmitting as soon as it detects that the energy is below the set threshold; and thus, when UEs served by different gNBs are adjacent to each other, simultaneous transmissions among multiple gNBs must collide. On the contrary, DRL based algorithms aiming for high rewards learn an effective strategy by trail-and-error to avoid collisions in a sense, although some UEs' data

TABLE I: Performances of various scheduling schemes in three-gNB scenarios.

Case (i)						
	DeepDS	DeepCS	FLDS	FLCS	dirLBT	omniLBT
Sum data rate of NR-U [Gbps]	17.80	17.23	19.30	18.75	12.45	11.36
Sum data rate of WiGig [Gbps]	4.16	4.02	2.56	2.40	4.28	5.29
Number of satisfied UEs	16	16	8	8	10	8
Case (ii)						
	DeepDS	DeepCS	FLDS	FLCS	dirLBT	omniLBT
Sum data rate of NR-U [Gbps]	19.60	19.06	21.20	20.63	14.52	13.60
Sum data rate of WiGig [Gbps]	4.10	3.94	2.46	2.30	4.23	5.29
Number of satisfied UEs	18	18	9	9	10	9

rate requirements will not be satisfied.

Overall, in the current work, the proposed algorithms only are targeted at maximizing the data rate of single NR-U network without causing excessive interference to the WiGig system, while guaranteeing the data rate requirements of all UEs. In our future work, we will further investigate how to cooperate agents in multi-gNB scenarios to avoid their decisions affecting each other.