

Efficient Feedback Mechanism and Rate Adaptation for LTE-based D2D Communication

Hoyoung Yoon, Seungil Park, and Sunghyun Choi

Department of ECE and INMC, Seoul National University, Seoul, Korea

Email: {hyyoon, spark11}@mwnl.snu.ac.kr, schoi@snu.ac.kr

Abstract—Along with the surge of data traffic amount, Long Term Evolution (LTE)-based Device-to-Device (D2D) communication is emerging as a key data traffic offloading technology. However, current LTE-based D2D communication has limitations such as the lack of feedback mechanism, causing difficulty for efficient radio resource use. In this paper, we propose a feedback mechanism as well as a feedback-based rate adaptation scheme to increase the spectral efficiency of LTE-based D2D communication. In particular, the proposed feedback mechanism between Transmitter (Tx) and Receivers (Rxs) is designed to minimize signaling overhead. Thanks to the feedback mechanism, the proposed rate adaptation scheme makes D2D Tx use the highest Modulation and Coding Scheme (MCS) level while guaranteeing reliable transmission to all Rxs. Through extensive simulations, we verify that the proposed solution achieves solid goodput performance under various channel environments.

I. INTRODUCTION

Along with the widespread use of smartphones and the development of wireless communication technologies, the amount of data traffic has soared dramatically. Cisco expects that global mobile data traffic will increase almost eightfold between 2015 and 2020 [1]. In order to support such increased traffic, Long Term Evolution (LTE)-based Device-to-Device (D2D) communication has been considered a key traffic offloading technology. Since User Equipments (UEs) communicate with other UEs directly, the spectral efficiency can be significantly enhanced.

In this paper, we consider D2D communication protocol recently developed in 3GPP [2].¹ In 3GPP D2D, only groupcast (or multicast)-based communication is supported, where D2D Transmitter (Tx) groupcasts data traffic to multiple D2D Receivers (Rxs) (belonging to the same group). However, feedback mechanism between D2D Tx and D2D Rxs is not defined. In fact, it is difficult to define a feedback mechanism without incurring high signaling overhead because multiple channels exist between D2D Tx and D2D Rxs. Due to the lack of feedback mechanism, D2D Tx cannot acquire the channel quality information, thus making it difficult to use radio resources efficiently.

We first propose feedback channel to support feedback mechanism between D2D Tx and D2D Rxs. In order for D2D Rxs to transmit feedback to D2D Tx, they need resources that are normally assigned and announced by Base Station (BS) or D2D Tx. The incurring signaling overhead should be proportional to the number of Rxs. In our feedback mechanism, the feedback resource location is implicitly determined by the resource location of the control signal from D2D Tx, which

is used for the announcement of the Tx's data transmission. By doing so, we completely remove the signaling overhead for feedback resource assignment. The proposed feedback channel also allows multiple D2D Rxs to transmit feedback in one Resource Block (RB)² using different cyclic shifted versions of a sequence, which have good auto-correlation property. Therefore, the proposed feedback channel can use radio resources efficiently.

On top of the proposed feedback mechanism, we also propose a rate adaptation algorithm for D2D communication. As mentioned above, D2D communication supports only groupcast. Considering the existence of multiple D2D Rxs, we aim to adjust Modulation and Coding Scheme (MCS) level according to the performance of the D2D Rx with the worst channel quality. The proposed rate adaptation algorithm is also designed in consideration of possible problems that can occur in D2D communication, e.g., in-band emission.

Our key contributions are summarized as follows:

- This is the first time a feedback mechanism for LTE-based D2D Tx and Rxs has been proposed, to our best knowledge.
- The proposed feedback mechanism does not require additional signaling for feedback scheduling and allows multiple D2D Rxs to use the same radio resource to improve spectral efficiency.
- We also propose a feedback-based rate adaptation scheme for D2D groupcast communication and verify that the proposed rate adaptation scheme achieves solid performance, e.g., goodput, in various channel environments.

The rest of the paper is organized as follows. Section II provides related work, and Section III describes the preliminaries. We present the system model in Section IV. Our proposed feedback mechanism is presented in Section V and the proposed rate adaptation is presented in Section VI. In Section VII, the proposed algorithm is evaluated via realistic, high-fidelity system-level simulations. Finally, we conclude our paper in Section VIII.

II. RELATED WORK

We classify related work into two parts, namely, D2D with feedback and multicast with rate adaptation.

A. D2D with Feedback

There are many studies [3]–[11], which support feedback mechanism as part of D2D communications. However, in most

¹We refer to LTE-based D2D communication as *D2D communication* for convenience for the rest of the paper.

²One RB consists of 84 resource elements, composed of 12 subcarriers and seven symbols.

studies [3]–[9], the authors assume the situation where BS receives feedback from D2D UEs while we support a feedback mechanism between D2D Tx and D2D Rx. Moreover, in most studies [3]–[10], it is assumed that cellular and D2D UEs share the same resource pool for data transmission. In contrast, in our work, D2D UEs do not share the resource pool with cellular UEs as defined in 3GPP LTE-based D2D communication. Zhou *et al.* [11] consider groupcast, but they assume that D2D Tx perfectly acquire data receiving result of all D2D Rx belonging to the same group. However, they do not provide any clear methodology of a feedback mechanism, thus making the work impractical.

B. Multicast with Rate Adaptation

The authors of [11] propose a rate adaptation scheme for D2D communication in groupcast scenarios. However, as mentioned above, satisfying the assumption should be difficult. Actually, very few studies have proposed rate adaptations for D2D communication. However, in other research areas, there are many papers for rate adaptation in multicast scenarios. (See the survey in [12], for example.)

In cellular networks, Araniti *et al.* [13] propose a subgrouping technique for multicast rate adaptation in LTE. The subgrouping technique is to group multicast Rx into subgroups of Rx experiencing similar channel quality for efficient data transmissions. In the downlink of cellular communications, BS is the only Tx. Therefore, the subgrouping based on channel quality between the fixed Tx, i.e., BS, and Rx does not incur a large overhead. However, in D2D communication, Tx is not fixed, but can change at any time. Therefore, the subgrouping technique can cause a large overhead in D2D communication since subgrouping is required every time Tx changes.

Gupta *et al.* [14] introduce multicast rate adaption schemes in Wireless Local Area Network (WLAN). The simplest multicast rate adaptation scheme introduced in the paper requires all Rx to transmit feedback. This approach is simple, but it is inefficient because all Rx should send feedback. Leader-based scheme and cluster-based scheme are introduced in [14] as techniques for solving such inefficiency. In leader-based scheme, a leader is elected, i.e., the Rx with the worst channel quality among all Rx becomes the leader, and the leader sends feedback to the access point (AP) on behalf of the group. In cluster-based scheme, clusters are created based on location, and the Rx with the worst channel quality in a cluster becomes the head of the cluster. The head transmits feedback to the AP on behalf of its cluster.

In WLAN, since the entity receiving feedback is fixed as AP, leader election and clustering do not incur large overhead. However, in D2D communication, as mentioned above, since the entity receiving feedback can be changed at any time, both cluster-based scheme and leader-based scheme can cause significant overhead.

III. PRELIMINARIES

A. Background for D2D

3GPP defines the basic framework for D2D communication as follows [2]. First, D2D uses dedicated physical resources,

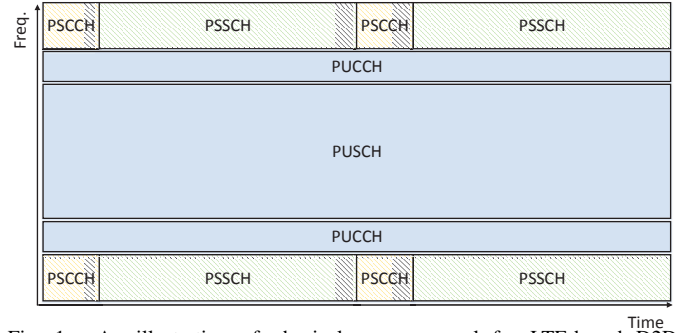


Fig. 1. An illustration of physical resource pool for LTE-based D2D communications.

separate from cellular uplink resources. Second, D2D supports only groupcast without feedback mechanism. To compensate for the absence of feedback mechanism, blind retransmission is adopted, i.e., Tx transmits packets repeatedly regardless of whether Rx receives the packets or not. 3GPP also defines physical channels for D2D. Fig. 1 shows an example of physical resource pool for cellular uplink resources. In Fig. 1, Physical Uplink Shared CHannel (PUSCH) for uplink data transmission is located in the middle of the frequency band and Physical Uplink Control CHannel (PUCCH) for control packet transmission is located at both ends of PUSCH.

Physical Sidelink Control CHannel (PSCCH) is additionally defined for Scheduling Assignment (SA) transmission in D2D communication. SA is control information periodically transmitted before data transmission and contains various types of information including group ID, MCS level, and resource location for data transmission. Physical Sidelink Shared CHannel (PSSCH) is also additionally defined for data transmission in D2D communication. In Fig. 1, PSCCH and PSSCH are located at both ends of PUCCH. The amount of resources for PSCCH and PSSCH is determined by the network operator. PSCCH and PSSCH regions are repeated periodically, where the length of the period (out of 40, 80, 160, and 320 ms) is again determined by the operator.

3GPP D2D supports two resource access modes. In mode 1, BS allocates resources, e.g., PSCCH and PSSCH, to D2D Tx requesting resource allocations. Therefore, in mode 1, there is no resource collision among D2D Tx. However, in mode 2, since D2D Tx randomly select resources within a predefined resource pool, there could be a resource collision among D2D Tx. SA transmitted via PSCCH contains essential information for data transmission and reception as stated above. Therefore, if D2D Rx does not receive SA due to resource collision, the D2D Rx can not receive data from D2D Tx in that period. In this paper, we consider mode 1 where all D2D UEs do not suffer from resource collision.

B. UE Behaviors in D2D

In mode 1 D2D, D2D UE behaves as follows. First, BS allocates resources, e.g., PSCCH and PSSCH, to D2D Tx. Through the allocated resources, the D2D Tx transmits both SA and data two and four times, respectively, due to the blind retransmission. Since D2D Rx does not know what resources the D2D Tx uses, the D2D Rx blindly decodes

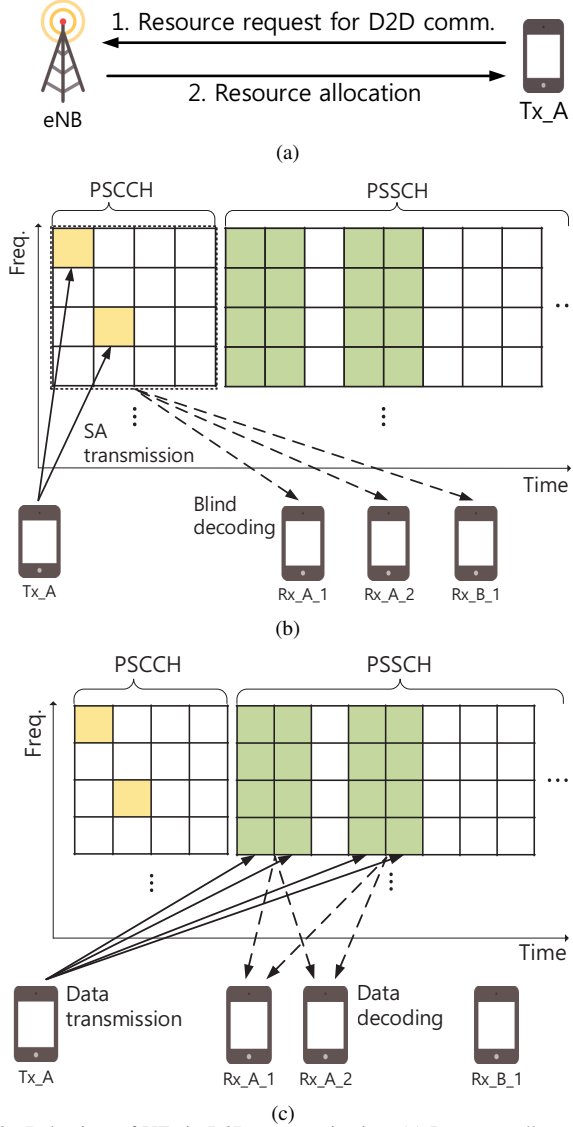


Fig. 2. Behaviors of UEs in D2D communication: (a) Resource allocation by infrastructure, (b) SA transmission and reception, and (c) Data transmission and reception.

PSCCH resource pool and checks if the group ID of the decoded SA matches its own ID. If they match, the D2D Rx decodes data based on the information in the SA. Otherwise, the D2D Rx waits until the next PSCCH resource pool.

For example, simply assume that there are two groups, i.e., groups A and B. Using Fig. 2, we explain D2D UE behaviors in D2D communication. Firstly, Fig. 2(a) shows that after the D2D Tx in group A requests resources, BS allocates resources to the D2D Tx. Fig. 2(b) shows that the D2D Tx transmits SA two times via assigned resources, and D2D Rxs blindly decode PSCCH resource pool and check the ID of the decoded SA. D2D Rxs in group A find the matching ID, while D2D Rx in group B does not. Therefore, Fig. 2(c) shows that D2D Rxs in group A decode data and D2D Rx in group B waits for the next PSCCH resource pool.

IV. SYSTEM MODEL

In this section, we explain the target system model assuming that D2D UEs communicate with each other. We consider

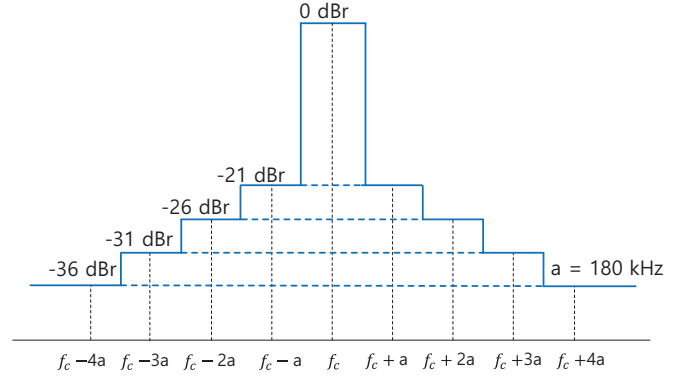


Fig. 3. Spectral mask of in-band emission.

multicell scenarios with 7 cells, where there are N D2D groups for each cell. Each D2D group consists of M D2D UEs, and D2D Txs groupcast data to their group members. In 3GPP standard [2], the groups, performing D2D communication, are formed in advance and the information of group formations is initially known through a D2D service authorization, which is mandatory to use D2D services. Accordingly, we assume that D2D UEs perform the D2D service authorization, and then acquire the information of their own groups.

We assume that D2D Txs in the same group do not transmit SA using the same time resource, i.e., the same subframe, in order to receive all SAs sent from the same group. Since we consider mode 1 D2D, in which BS allocates resources to D2D Txs, the assumption is feasible. Resource pools, e.g., PSCCH and PSSCH, are periodically repeated, and we assume that the period is 80 ms, one of the options in the 3GPP standard.

We also consider in-band emission, which is unwanted power leakage from the allocated bandwidth for transmission to the unallocated bandwidth within the total bandwidth used by the network operator. Fig. 3 shows spectral mask of in-band emission caused by transmission via one RB, i.e., bandwidth of 180 kHz, according to Clause A.2.1.5 of [15]. As shown the figure, at the ± 180 kHz from the center frequency, i.e., f_c , transmission power is attenuated by 21 dB, i.e., the RBs closest to the allocated RB experience 21 dB attenuated power leakage at the transmission power. The farther away from the center frequency, the less the unwanted power leakage. Thus, RBs adjacent to the assigned RB are more susceptible to in-band emission.

In the uplink of cellular communication, BS is the only Rx. Since BS can adjust transmission power of a UE based on the channel quality between BS and the UE, received power levels at BS can be similar. Therefore, in-band emission problem is not severe in cellular communication because the ratio of the attenuated power incurred by in-band emission to the power of the target signal can be relatively small. However, in D2D communication, unlike the uplink of cellular communication, there are multiple D2D Rxs. Since it is difficult to control transmission power based on any one D2D Rx, D2D Tx transmits signal with maximum power, i.e., 23 dBm. As a result, the ratio of the attenuated power incurred by in-band emission to the power of the target signal can be large enough to affect D2D communication. We use a realistic system

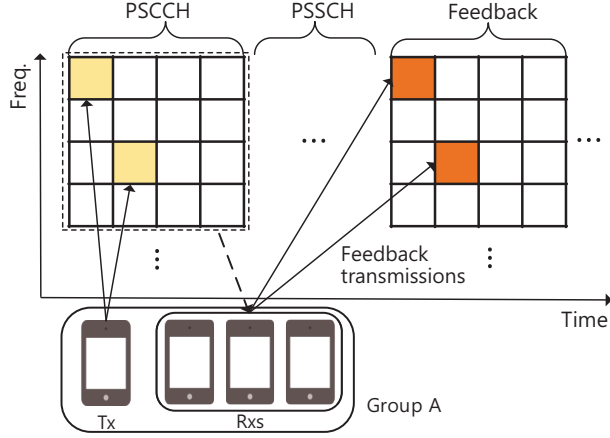


Fig. 4. An example of the proposed feedback mechanism for D2D communication.

model to evaluate the impact of in-band emission in D2D communication.

V. FEEDBACK MECHANISM

We consider two philosophies for designing a feedback channel for D2D. First, we try to allocate as few resources as possible to the feedback channel in order to minimize the waste of resources used for the feedback channel. Second, D2D Rx should be able to use the proposed feedback mechanism regardless of its connection with BS. In general, D2D Rxs do not need to be connected to BS because they can directly receive data from D2D Txs. Therefore, feedback mechanisms that can be used only through BS are not desirable.

We propose that D2D Rxs transmit feedback using the RBs at the same positions as SAs transmitted by the D2D Tx belonging to the same group. Fig. 4 shows an example of our proposed feedback mechanism. As shown in the figure, D2D Tx transmits SA containing the information for data reception twice via PSCCH, and D2D Rxs, belonging to the same group, blindly decode PSCCH resource pool and receive two SAs transmitted by the D2D Tx. Since the position of feedback resource is the same as the position of the SA transmitted in the same group, the D2D Rxs transmit the feedback at the received SA resource locations without additional signaling, i.e., without additional signaling, two RBs are assigned to D2D Rxs and D2D Rxs transmit the feedback.

In order to allow multiple D2D Rxs to use the limited feedback resources, i.e., two RBs, we use cyclic shifted versions of a sequence with good auto-correlation property. When such a sequence is cyclic shifted, the shifted sequence and the original sequence are nearly orthogonal. By using the property, up to 12 D2D Rxs can use one RB simultaneously.³ Therefore, when D2D Rxs transmit feedback only once, 24 D2D Rxs can transmit feedback using two RBs. Since 3GPP considers the number of group members to be around 10 in general scenarios [15], the proposed feedback channel should be able to support all the group members.

³Since one RB spans 12 subcarriers, a sequence of length 12 is used for one RB.

There are two issues, which we have to address. The first issue is near-far problem since the proposed feedback channel allows multiple D2D Rxs to use the same resources at the same time. We briefly explain near-far problem through an example. Near D2D UE and far D2D UE transmit feedback to a D2D Tx via the same feedback resource. Then the D2D Tx receives feedback and conducts AGC. In AGC, both feedback signals are multiplied by a common gain. The common gain depends on the strong signal because the received signal must not go out of the dynamic range of the ADC. At that time, the weak signal might become indistinguishable from quantization noise because the weak signal becomes too small.

We apply Open Loop Power Control (OLPC) to D2D communications to mitigate near-far problem. Through OLPC, D2D Rxs adjust transmission power based on the strength of the received signal from D2D Tx belonging to the same group. Through simulation results in Section VII, we confirm the effect of near-far problem on the proposed feedback channel and how the effect of near-far problem on the proposed feedback channel changes when OLPC is applied.

As mentioned in Section IV, the in-band emission is the second issue. Since the proposed feedback channel allows multiple D2D Rxs to use one RB, the in-band emission caused by multiple D2D Rxs can accumulate. Therefore, D2D Tx may fail to receive feedback due to an accumulated in-band emission. On top of the proposed feedback channel, we propose a groupcast rate adaptation algorithm, which tries to mitigate the damage caused by the accumulated in-band emission.

The proposed feedback mechanism has several advantages. Above all, since feedback resources are assigned to D2D Rxs via SAs sent from the same group, D2D Rxs can use the proposed feedback mechanism without the help of BS. Therefore, no additional signaling is required for feedback scheduling. Second, the overhead of using feedback resources can be reduced because multiple D2D Rxs transmit feedback using one RB. In summary, we propose an efficient feedback mechanism that minimizes the overhead, i.e., the amount of feedback resources, and signaling for feedback resource scheduling.

VI. GROUPCAST RATE ADAPTATION ALGORITHM

On top of the proposed feedback channel, we propose a groupcast rate adaptation algorithm, called Fast and Robust Rate Adaptation (FaRRRA) algorithm. FaRRRA is an algorithm for D2D Rxs to effectively transmit feedback while trying to reduce in-band emission in the proposed feedback channel. In FaRRRA algorithm, D2D Rxs, which want to raise MCS level, opportunistically transmit feedback to reduce in-band emission. However, D2D Rxs desiring to lower MCS level transmit feedback twice so that D2D Tx can receive the feedback successfully. FaRRRA algorithm conservatively operates by giving the priority to feedback requesting to lower MCS level in order to satisfy all group members, and tries to increase the spectral efficiency, e.g., bits/Hz, by making D2D Rxs opportunistically transmit feedback requesting to raise MCS level.

TABLE I
NOTATIONS AND PARAMETERS USED IN PSEUDO CODES.

Symbol	Definition
$SA_{i,j}$	SA located at i th subframe and j th RB
$MCS_{i,j}$	MCS level within $SA_{i,j}$
$ID_{i,j}$	Group ID within $SA_{i,j}$
ID_m	Group ID of the m th D2D UE
M_n	MCS level used in n th period
$FM_{n,m}$	MCS level from the m th UE in n th feedback transmission
N_{time_PSCCH}	The number of subframes for PSCCH
N_{freq_PSCCH}	The number of RBs at a given subframe for PSCCH
FI	Feedback sensing indicator
γ_{data}	SINR of received data
fm	Maximum supportable MCS level
K	The number of group members
Th	BLER threshold
F_{rsc1st}	Set of feedback successfully received via 1st feedback resource
F_{rsc2nd}	Set of feedback successfully received via 2nd feedback resource
F	Set, combined F_{rsc1st} and F_{rsc2nd}

Algorithm 1 Rx's behavior of FaRRRA algorithm

Set:
1: $FI = 0$ ▷ feedback sensing indicator
2: $fm = 0$ ▷ supportable MCS level
3: m ▷ ID of D2D Rx in consideration
During n th SA transmission:
4: **for** $i \leftarrow 1, \dots, N_{time_PSCCH}$ **do**
5: **for** $j \leftarrow 1, \dots, N_{freq_PSCCH}$ **do**
6: **if** $ID_m == ID_{i,j}$ **then**
7: receive SA
8: $M_n \leftarrow MCS_{i,j}$
9: **end if**
10: **end for**
11: **end for**
During n th data transmission:
12: **if** receive SA **then**
13: receive data
14: $\gamma \leftarrow E[\gamma_{data}]$
15: **while** $TBLER(\gamma, fm) \leq Th$ **do**
16: $fm = fm + 1$
17: **end while**
18: $FM_{n,m} \leftarrow fm$
19: **end if**
During n th feedback transmission:
20: **if** $FM_{n,m} \geq M_n + 1$ **then**
21: monitor 1st feedback resource
22: **if** sense feedback of receivers **then**
23: $FI = 1$
24: **end if**
25: **if** $FI == 0$ **then**
26: transmit feedback via 2nd feedback resource
27: **end if**
28: **else**
29: **if** $FM_{n,m} < M_n + 1$ && $FM_{n,m} \geq M_n$ **then**
30: transmit feedback via 1st feedback resource
31: **else**
32: transmit feedback via 1st and 2nd feedback resources
33: **end if**
34: **end if**

Table I lists notations and parameters used in the pseudo codes for algorithms. Algorithm 1 provides the behavior of D2D Rx with FaRRRA algorithm. The D2D Rx sets FI and fm to 0 before the n th period begins (lines 1–2). During the n th SA transmission (lines 4–11), the D2D Rx blindly decodes the entire PSCCH resource pool and compares the ID of the decoded SA with its own ID. If there is an SA with the ID matching its own ID, the D2D Rx fully receives SA and checks

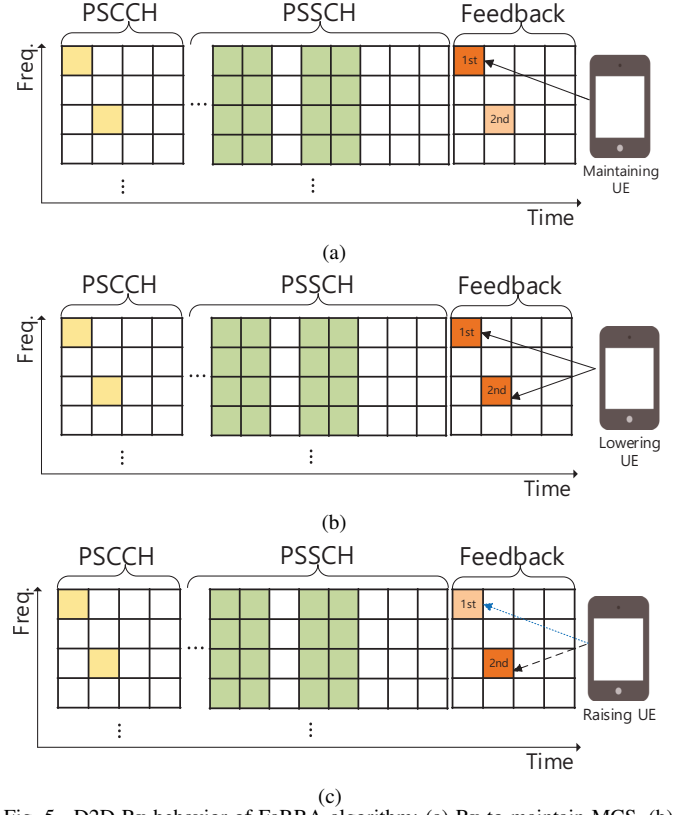


Fig. 5. D2D Rx behavior of FaRRRA algorithm: (a) Rx to maintain MCS, (b) Rx to lower MCS, and (c) Rx to raise MCS.

the information in the SA including MCS level and resource location of data transmission. During the n th data transmission (lines 12–19), the D2D Rx receives data via PSSCH. The D2D Rx determines the average SINR of the received data, and finds the highest MCS level that limits Transport Block Error Rate (TBLER), which is the ratio of the number of erroneous transport blocks (TBs) to the total number of TBs, to the predefined threshold. The D2D Rx calculates TBLER using MCS level and the average SINR of data signal, i.e., γ , and the highest MCS level is fed back by the D2D Rx to D2D Tx.

During the n th feedback transmission (lines 20–34), D2D Rx is classified into one of three types, i.e., D2D Rx which wants to raise MCS level, that to maintain MCS level, and that to lower MCS level. In case of D2D Rx, desiring to raise MCS level (lines 20–27), the D2D Rx monitors whether other D2D Rxs send feedback via the first feedback resource (in the chronological order). If feedback from another D2D Rx is detected, FI is set to 1 and the D2D Rx does not transmit feedback in the n th feedback transmission. Otherwise, the D2D Rx sends $FM_{n,m}$ to D2D Tx via the second feedback resource. In case of D2D Rx, desiring to maintain MCS level (lines 28–30), the D2D Rx transmits $FM_{n,m}$ to D2D Tx via only the first feedback resource. D2D Rx, which wants to lower MCS level, always transmits $FM_{n,m}$ to D2D Tx two times by using both the first and second feedback resources.

Because D2D supports only groupcast, feedback requesting to lower MCS level is given the highest priority while feedback requesting to raise MCS level is given the lowest priority to support all the group members reliably. Therefore, in

Algorithm 2 Tx's behavior of FaRRa algorithm

Set:

- 1: M_n ▷ MCS level used in n th period
- 2: K ▷ the number of group members
- 3: $F_{rsc1st} = \emptyset$ ▷ received feedback set
- 4: $F_{rsc2nd} = \emptyset$ ▷ received feedback set

During n th feedback transmission via 1st feedback resource:

- 5: **if** receive feedback of k th Rx **then**
- 6: $F_{rsc1st} \ni FM_{n,k}$
- 7: **end if**

During n th feedback transmission via 2nd feedback resource:

- 8: **if** receive feedback of k th Rx **then**
- 9: $F_{rsc2nd} \ni FM_{n,k}$
- 10: **end if**

Rate adaptation for $(n+1)$ th period:

- 11: **if** $F_{rsc1st} == \emptyset$ **then**
- 12: **if** $\|F_{rsc2nd}\| == K$ **then**
- 13: $M_{n+1} \leftarrow \min(F_{rsc2nd})$
- 14: **else**
- 15: $M_{n+1} \leftarrow M_n + 1$
- 16: **end if**
- 17: **else**
- 18: **if** $F_{rsc2nd} == \emptyset$ **then**
- 19: $M_{n+1} \leftarrow M_n$
- 20: **else**
- 21: $F \leftarrow \text{combining } F_{rsc1st} \text{ and } F_{rsc2nd}$
- 22: $M_{n+1} \leftarrow \min(F)$
- 23: **end if**
- 24: **end if**

Algorithm 3 Rx's behavior of RO algorithm

During n th SA transmission:

- 1: **for** $i \leftarrow 1, \dots, N_{time_PSCCH}$ **do**
- 2: **for** $j \leftarrow 1, \dots, N_{freq_PSCCH}$ **do**
- 3: **if** $ID_m == ID_{i,j}$ **then**
- 4: receive SA
- 5: $M_n \leftarrow MCS_{i,j}$
- 6: **end if**
- 7: **end for**
- 8: **end for**

During n th data transmission:

- 9: **if** receive SA **then**
- 10: receive data
- 11: $\gamma \leftarrow E[\gamma_{data}]$
- 12: **while** $TBLER(\gamma, fm) \leq Th$ **do**
- 13: $fm = fm + 1$
- 14: **end while**
- 15: $FM_{n,m} \leftarrow fm$
- 16: **end if**

During n th feedback transmission:

- 17: **if** $\text{mod}(n, 2) == 1$ **then** ▷ lowering turn
- 18: **if** $FM_{n,m} < M_n$ **then**
- 19: transmit feedback
- 20: **end if**
- 21: **else** ▷ raising turn
- 22: **if** $FM_{n,m} < M_n \parallel FM_{n,m} == M_n$ **then**
- 23: transmit feedback
- 24: **end if**
- 25: **end if**

FaRRa algorithm, D2D Rx, desiring to lower MCS level, preferentially transmit their own feedback two times via two feedback resources. Feedback requesting to raise MCS level becomes meaningless if D2D Tx receives feedback requesting to lower or maintain MCS level. In this case, if feedback requesting to raise MCS level is transmitted, it just worsens in-band emission problem. Accordingly, D2D Rx, which want to raise MCS level, transmit their feedback via the second feedback resource only when the feedback is meaningful.

Fig. 5 shows an example for feedback transmission of D2D Rx. Firstly, feedback resources, i.e., two RBs, are assigned to D2D Rx by SA sent from D2D Tx. Fig. 5(a) shows feedback transmission of D2D Rx, desiring to maintain MCS level in FaRRa algorithm. Since feedback requesting to maintain MCS level can be expressed in a single bit, there is less need to increase SINR of the feedback for successfully decoding the feedback. Therefore, the D2D Rx transmits feedback via only the first feedback resource. It also helps relieve in-band emission problem by decreasing the number of feedback transmissions. As shown in Fig. 5(b), D2D Rx, desiring to lower MCS level, transmits feedback twice using two feedback resources to increase SINR of the feedback because the improved SINR of the feedback increases the probability of successfully feedback decoding by D2D Tx.

The behavior of D2D Rx, desiring to raise MCS level, is shown in Fig. 5(c). First, the D2D Rx monitors the first feedback resource to check the transmission of feedback requesting to lower or maintain MCS level. If the D2D Rx senses such feedback, the D2D Rx abandons transmission of its feedback requesting to raise MCS level in order to avoid unnecessary in-band emission due to the second feedback resource. Otherwise,

the D2D Rx transmits feedback requesting to raise MCS level via the second feedback resource.

Algorithm 2 provides a description of the D2D Tx behavior in FaRRa algorithm. D2D Tx determines M_n , checks K , and sets F_{rsc1st} and F_{rsc2nd} to empty sets before the n th period begins (lines 1–4). During the n th feedback transmission via the first feedback resource (lines 5–7), the received feedback is put into F_{rsc1st} . On the contrary, the received feedback via the second feedback resource is put into F_{rsc2nd} (lines 8–10).

During rate adaptation for the $(n+1)$ th period (lines 11–24), D2D Tx first checks F_{rsc1st} . If F_{rsc1st} is an empty set, the D2D Tx checks F_{rsc2nd} . If the cardinality of F_{rsc2nd} is the same as the number of group members, the D2D Tx adapts the lowest MCS level based on F_{rsc2nd} (lines 11–13). Otherwise (lines 14–16), it means that the D2D Tx did not receive feedback from all D2D Rx in the group. Therefore, in this case, the D2D Tx conservatively raises MCS level by one. If F_{rsc1st} is not an empty set, there exist demands for lowering or maintaining the current MCS level (lines 17–24). When F_{rsc2nd} is an empty set, the D2D Tx maintains the MCS level because there are only D2D Rx, which want to maintain MCS level (lines 18–19). Otherwise, F_{rsc1st} and F_{rsc2nd} are combined to increase the SINR of the feedback signal, and then the D2D Tx determines the lowest MCS level based on F , obtained by combining F_{rsc1st} and F_{rsc2nd} (lines 20–24).

We additionally consider two more algorithms to compare with FaRRa algorithm. The first comparison algorithm is In-band Emission (IE) algorithm, in which all D2D Rx send feedback through feedback resources regardless of the purpose, i.e., lowering, maintaining, or raising MCS level, and D2D Tx selects MCS level for the next period based

Algorithm 4 Tx's behavior of RO algorithm

Set:
 1: $F = \emptyset$ ▷ received feedback set
 2: K ▷ the number of group members
During n th feedback transmission via 1st feedback resource:
 3: **if** receive feedback of k th Rx **then**
 4: $F_{rsc1st} \ni FM_{n,k}$
 5: **end if**
During n th feedback transmission via 2nd feedback resource:
 6: **if** receive feedback of k th Rx **then**
 7: $F_{rsc2nd} \ni FM_{n,k}$
 8: **end if**
 9: $F \leftarrow \text{combining } F_{rsc1st} \text{ and } F_{rsc2nd}$
During rate adaptation for $(n+1)$ th period:
 10: **if** $\text{mod}(n, 2) == 1$ **then** ▷ lowering turn
 11: **if** $F! = \emptyset$ **then**
 12: $M_{n+1} \leftarrow \min(F)$
 13: **else**
 14: $M_{n+1} \leftarrow M_n$
 15: **end if**
 16: **else** ▷ raising turn
 17: **if** $F! = \emptyset$ **then**
 18: $M_{n+1} \leftarrow \min(F)$
 19: **else**
 20: **if** $M_n == 28$ **then**
 21: $M_{n+1} \leftarrow M_n$
 22: **else**
 23: $M_{n+1} \leftarrow M_n + 1$
 24: **end if**
 25: **end if**
 26: **end if**

on the received feedback. FaRRRA algorithm tries to reduce the number of D2D Rxs transmitting feedback as much as possible considering the damage caused by in-band emission. On the other hand, the number of feedback-transmitting Rxs remains constant with IE algorithm, i.e., all D2D Rxs always transmit feedback during the period of feedback transmission. We compare the effectiveness of FaRRRA algorithm, which reduces the number of D2D Rxs transmitting feedback, with IE algorithm.

The second comparison algorithm is Robustness Oriented (RO) algorithm, which focuses on successful data reception of all members. Algorithm 3 provides a description of the D2D Rx behavior in RO algorithm. During the n th SA and data transmissions (lines 1–16), RO algorithm work in the same way as FaRRRA algorithm. However, in RO algorithm, two turns alternate, i.e., MCS level lowering turn and MCS level raising turn. If n is an odd (even) number, the n th feedback transmission is the lowering (raising) turn. If the n th feedback transmission is the lowering turn, only D2D Rxs, desiring to lower MCS level, transmit feedback (lines 17–20). Otherwise (lines 22–24), both types of D2D Rxs, i.e., desiring to lower and desiring to maintain, transmit feedback. RO algorithm reduces the impact of in-band interference because D2D Rxs, which want to raise MCS level, do not transmit feedback.

Algorithm 4 provides a description of the D2D Tx behavior in RO algorithm. D2D Tx checks K and sets F to an empty set before the n th period begins (lines 1–2). During the n th feedback transmission (lines 3–9), the D2D Tx receives feedback via the first and second feedback resources and makes F , obtained by combining F_{rsc1st} and F_{rsc2nd} . For rate

TABLE II
SIMULATION ENVIRONMENTS.

Carrier frequency	2 GHz
System bandwidth	10 MHz (50 RBs)
Topology	Uniform distribution
Channel model	Fast fading + shadowing + pathloss + in-band emission [15]
The number of bits for ADC	12 bits
Transmission power	23 dBm
Noise figure	9 dB
Noise power	−174 dBm/Hz

adaptation in the $(n+1)$ period, if n is an odd number and F is not an empty set, the D2D Tx selects the lowest MCS level based on F (lines 10–12). If n is an odd number and F is an empty set, the D2D Tx maintains MCS level (lines 13–15). If n is an even number and F is not an empty set, the D2D Tx selects the lowest MCS level based on F because there are demands on lowering or maintaining MCS level (lines 16–18). However, if n is an even number and F is an empty set, the D2D Tx raises MCS level by one because all members agree to raise MCS level (lines 19–25).

FaRRRA algorithm tries to reduce the amount of in-band emission by transmitting feedback requesting to raise MCS level opportunistically. However, RO algorithm has a large advantage in reducing the amount of in-band emission because D2D Rxs, which want to raise MCS level, do not transmit feedback at all at the cost of delayed MCS level increase. We investigate the robustness of FaRRRA algorithm over in-band emission by comparing FaRRRA algorithm with RO algorithm.

VII. PERFORMANCE EVALUATION

In this section, we evaluate the impact of near-far problem over the proposed feedback channel and the performance of FaRRRA algorithm. We follow the evaluation methodology in Annex A.2 of [15] for our system level simulation using MATLAB. In this simulation, we assume that the system bandwidth is 10 MHz, which can accommodate up to 50 RBs in frequency domain, and the period is 80 ms consisting of 4 ms for PSCCH and feedback and 72 ms for PSSCH.

A. Simulation Environments

Table II summarizes the simulation environments, and details are described below.

Topology: We consider multicell scenarios with seven cells and the radius of each cell is 150 m. There are three groups of UEs in each cell. A group consists of one Tx and nine Rxs. Txs are randomly distributed in a cell. Rxs are also randomly distributed around the Tx belonging to the same group.

Channel model: We consider fast fading generated using ITU-R IMT UMi model [16]. We also create shadowing following a log-normal distribution with standard deviation of 3 dB as specified in Clause A.2.1.2 of [15]. Pathloss is calculated using WINNER+B1 model [17]. Finally, in-band emission is also generated according to Clause A.2.1.5 of [15].

Near-far problem: The proposed feedback channel allows multiple Rxs to use the same feedback resource. Therefore, when near Rxs and far Rxs (from a given Tx) transmit feedback simultaneously, the Tx can suffer from near-far

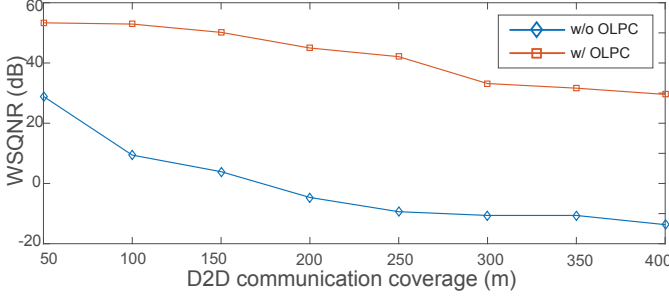


Fig. 6. Impacts of near-far problem.

problem. All received signals are multiplied by a common gain and enter Analog-to-Digital Converter (ADC), which uses 12 bits to quantize signals. Quantization level is determined by the sum of power levels of received signals, and determines quantization noise. Throughout simulations, we consider the quantization noise when calculating SINR.

B. Impact of Near-Far Problem

We first evaluate the impact of near-far problem on the proposed feedback channel. For simplicity, we assume that there are one D2D Tx and two D2D Rx, i.e., a near D2D Rx and a far D2D Rx, and then the D2D Rxs transmit feedback via the same feedback resource. We consider a performance metric, called Weakest received Signal strength to Quantization Noise Ratio (WSQNR), which is the ratio of signal strength of the far D2D Rx to quantization noise. Since the signal from the far D2D Rx is more susceptible to the quantization noise than that of the near D2D Rx, it is meaningful to check WSQNR performance.

Fig. 6 shows the WSQNR performance both when OLPC is applied and when it is not, depending on D2D communication coverage, which means the radius in which D2D Tx can handle D2D communication. We first observe that the WSQNR performance unacceptably degrades, e.g., even under 0 dB, as the D2D communication coverage increases when OLPC is not employed. Therefore, without OLPC, it is difficult to use the proposed feedback channel, especially, when we target large D2D communication coverage. On the other hand, when OLPC is employed, the WSQNR performance is greatly improved. Accordingly, we conclude that OLPC should be applied to increase D2D communication coverage.

C. Comparison of Algorithms

Now, we evaluate FaRRRA algorithm in comparison with IE and RO algorithms. Fig. 7(a) shows that each algorithm adapts MCS level every period. The blue line with diamond markers represents the highest achievable MCS level that D2D Rx with the worst channel quality can support. Therefore, to satisfy all Rx, MCS level should be chosen smaller than or equal to the MCS level pointed by the diamond marker at each period. We observe that IE algorithm does not properly adjust MCS level by choosing MCS level higher than the highest achievable MCS level many times. It means that in-band emission caused by feedback transmissions of all D2D Rx has a severely negative impact on the reception of feedback by D2D Tx.

In case of FaRRRA and RO algorithms, we observe that most MCS values are less than or equal to the highest achievable

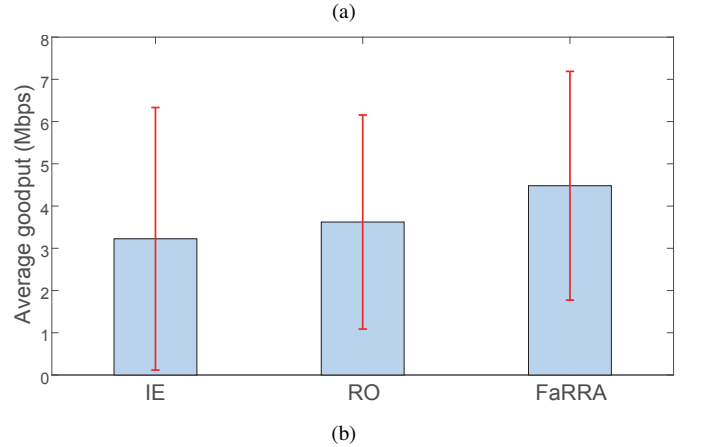
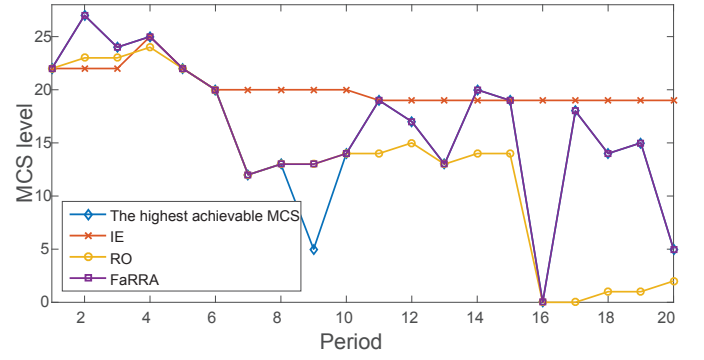


Fig. 7. Comparison of the algorithms: (a) MCS adaptation over time and (b) goodput performance of the worst channel Rx.

MCS level. However, in RO algorithm, since D2D Rx does not transmit the feedback requesting to raise MCS level, it does not use resources efficiently. On the other hand, FaRRRA algorithm uses resources more efficiently because D2D Rx opportunistically transmits feedback requesting to raise MCS level.

Fig. 7(b) shows the average goodput performance of the three algorithms. In case of unicast, goodput is the throughput that Rx successfully received, i.e.,

$$\text{Goodput} = \frac{\# \text{ received blocks} \times \text{block size}}{\text{Period length}} \text{ (bps)}.$$

However, we evaluate the throughput that the D2D Rx with the worst channel quality achieves because we consider groupcast scenarios, i.e., we evaluate the goodput of the D2D Rx, which has the worst channel quality in a group. In Fig. 7(b), FaRRRA algorithm achieves higher goodput than the other algorithms. The red bars in Fig. 7(b) represent standard deviations. The standard deviation of FaRRRA algorithm is slightly larger than that of RO algorithm because FaRRRA algorithm is capable of supporting larger MCS level increase compared to RO algorithm. In summary, FaRRRA algorithm is as robust as RO algorithm, and, at the same time, it quickly adjusts MCS level, thus enabling more efficient use of radio resources.

D. Comparison of FaRRRA Algorithm and Legacy Scheme

In this subsection, we compare FaRRRA algorithm with the legacy scheme using a fixed MCS level. In the legacy scheme, D2D Tx transmits data using a fixed MCS level, e.g., MCS 6,

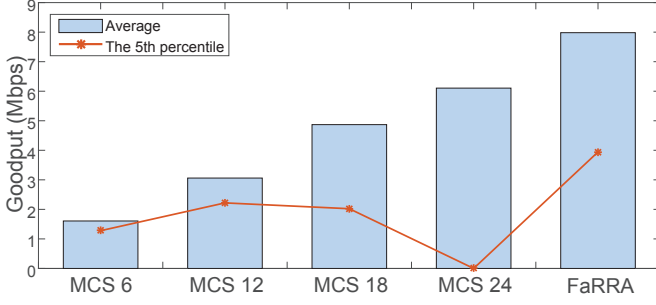


Fig. 8. Overhead caused by feedback mechanism.

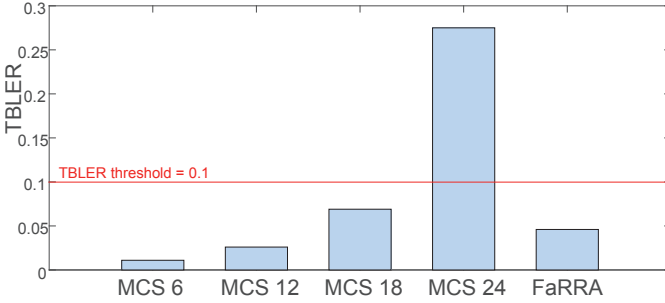


Fig. 9. Transport block error rate.

12, 18, or 24 during PSSCH. In case of the legacy scheme, 4 ms and 76 ms are for PSSCH and PSSCH, respectively. On the other hand, in FaRRR algorithm, D2D Tx adapts MCS level every period, and transmits data for 72 ms since the proposed feedback channel is added, i.e., the reduced 4 ms is for the proposed feedback channel.

Fig. 8 shows the goodput obtained by averaging the results from 100 simulation runs. We observe that FaRRR algorithm outperforms the legacy schemes while the legacy scheme with high MCS level tends to achieve higher average goodput. We also observe the 5th percentile goodput, representing the average of the bottom 5% of all goodput performances. We observe that the 5th percentile goodput of the legacy scheme with MCS 24 is almost zero. This demonstrates the limitation of the legacy scheme, which uses a fixed MCS level irrespective of the channel variation.

The reason why fixed MCS 24 achieves such a bad 5th percentile goodput becomes clearer by evaluating the TBLER performance. Fig. 9 shows the result of TBLER for both FaRRR and the legacy schemes. We first observe that the TBLER of fixed MCS 24 is over 0.25, thus resulting in almost zero 5th percentile goodput. For fixed MCSs 6 and 12, although they have good TBLER performance, the 5th percentile and the average goodput performances are low due to small transport block sizes. Therefore, it is difficult to use radio resources efficiently in those cases. On the other hand, FaRRR algorithm works properly by keeping the TBLER under the threshold, which is set to 0.1. That is, our simulation results demonstrate that FaRRR algorithm uses radio resources efficiently while keeping TBLER under the threshold.

VIII. CONCLUDING REMARKS

We proposed a feedback mechanism for LTE-based D2D communication. The proposed feedback mechanism efficiently uses radio resources by allowing multiple D2D RxS to use one RB at the same time without requiring extra signaling for feedback scheduling. We also propose FaRRR algorithm, a rate adaptation algorithm considering the impact of in-band emission. Through simulations, we evaluate the impacts of near-far problem to the proposed feedback channel and demonstrate that the near-far problem is greatly mitigated by applying OLPC. We also find that FaRRR algorithm is robust to in-band emission and uses radio resources more efficiently than the legacy schemes while keeping TBLER under the threshold.

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