Efficient Feedback Mechanism for LTE-based D2D Communication

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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 to increase the spectral efficiency of LTE-based D2D communication. In particular, the proposed feedback mechanism is designed to minimize signaling overhead and D2D Rxs can use the proposed feedback mechanism without any connection to Base Station (BS). On top of the proposed mechanism, we also propose feedback-aided rate adaptation and recovery schemes. Through extensive simulations, we verify that the proposed solutions achieve solid performances, e.g., goodput and latency, under various channel environments.

Keywords: Device-to-device communication, multicast, data offloading, feedback mechanism

1. 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]. 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).

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We refer to LTE-based D2D communication as D2D communication for convenience for the rest of the paper.
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 channel states 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 propose a rate adaptation algorithm for D2D communication. As mentioned above, D2D communication supports only groupcast. Considering the existence of multiple D2D Rxs, the proposed rate adaptation algorithm aims to adjust Modulation and Coding Scheme (MCS) level depending on 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. In order for the proposed feedback mechanism to be applied to various applications, we show that the our proposed feedback mechanism can allow packet recovery by request.

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 algorithm for D2D groupcast communication and verify that the proposed solutions achieve solid performance, e.g., goodput, in

\(^2\)One RB consists of 84 resource elements, composed of 12 subcarriers and seven symbols.
various channel environments.

- We propose a recovery scheme for D2D groupcast communication and show that the proposed scheme achieves solid performances, e.g., goodput and latency.

The rest of the paper is organized as follows. Section 2 provides related work, and Section 3 describes the preliminaries. We present the system model in Section 4. Our proposed feedback mechanism is presented in Section 5 and the proposed rate adaptation is presented in Section 6. Our proposed recovery scheme is presented in Section 7. In Section 8, the proposed algorithm is evaluated via realistic, high-fidelity system-level simulations. Finally, we conclude our paper in Section 9.

2. Related Work

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

2.1. D2D with Feedback

There are many studies, which support feedback mechanism while considering D2D communications as part of cellular communication system [3, 4, 5, 6, 7, 8, 9, 10, 11]. However, in most studies, 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, the authors assume that cellular and D2D UEs share the same resource pool for data transmission and they only consider unicast scenarios despite the fact that LTE-based D2D communication supports groupcast only [3, 4, 5, 6, 7, 8, 9, 10]. In contrast, in our work, D2D UEs do not share the resource pool with cellular UEs as defined in 3GPP LTE-based D2D communication and groupcast scenarios are considered. Zhou et al. [11] consider groupcast, but they assume that D2D Txs perfectly acquire data receiving result of all D2D Rxs belonging to the same group. However, they do not provide any clear methodology of a feedback mechanism, thus making the work impractical. Through our work, we propose a feasible feedback mechanism for D2D communication considering the 3GPP standard.

2.2. 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 Rxs into subgroups of Rxs 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 Rxs 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 Rxs to transmit feedback. This approach is simple, but it is inefficient because all Rxs 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 Rxs 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.

2.3. Multicast with Retransmission

There are studies considering retransmission of D2D communications [15, 16, 17, 18]. However, in [15, 16], the authors assume the situation where D2D UEs retransmit packets for cellular downlink traffic. On the other hand, we consider retransmission for D2D data traffic, which is generated by D2D UEs. In [17, 18], the authors consider retransmission via relay node. Khoueiry et al. [17] propose a network coding strategy to enhance multicast performance. However, the authors of [17] consider that topology is fixed and relay node is also fixed. As mentioned above, in D2D communications, Tx is not fixed, but can change at any time. Therefore, fixed relay node is impractical since the quality of radio channel changes whenever Tx changes.

Zhou et al. [18] propose D2D relay algorithm and the authors of [18] consider that D2D UEs, which receive data packets, retransmit the data packets. Hence, the algorithm proposed by Zhou
requires resource allocations for the potential relay nodes. Therefore, the solution might be not scalable if there are many UEs.

Many studies consider network coding for efficient retransmission assuming that the links, i.e., radio resources, between Tx and all Rxs are already setup [19, 20, 21, 22, 23, 24]. Therefore, Rx transmits feedback for retransmission request via allocated link and then Tx efficiently retransmits encoded packets based on feedback. However, the assumption that radio resources for feedback are already setup should be infeasible because resource allocations for D2D Rxs are not scalable if there are many D2D Rxs. Through our work, we propose a retransmission scheme that operates on the proposed feedback mechanism considering scalable resource allocation.

3. Preliminaries

3.1. Background for D2D

3GPP defines the basic framework for D2D communication as follows [2]. First, D2D uses dedicated physical resources, 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. 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 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. PSCCH and PSSCH are located at both ends of Physical Uplink Control CHannel (PUCCH), which is dedicated to control packet transmission for uplink. PSCCH and PSSCH regions are repeated periodically, where the length of the period is out of 40, 80, 160, and 320 ms.

3GPP D2D supports two resource access modes. In mode 1, BS allocates resources, e.g., PSCCH and PSSCH, to D2D Txs requesting resource allocations. Therefore, in mode 1, there is no resource collision among D2D Txs. However, in mode 2, since D2D Txs randomly select resources within a predefined resource pool, there could be a resource collision among D2D Txs. 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 cannot receive data from D2D Tx in that period. In this paper, we consider that resource allocations
for SA only supports mode 1, but, resource allocations for D2D data can support both modes 1 and 2.

3.2. UE Behaviors in 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 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 decoded SA. Otherwise, the D2D Rx waits until the next PSCCH resource pool.

Using Fig. 1, we explain D2D UE behaviors in D2D communication. There are two groups, i.e., groups A and B. Firstly, BS allocates resources, e.g., PSCCH and PSSCH, to D2D Tx in group A. Fig. 1(a) 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. 1(b) shows that D2D Rxs in group A decode data and D2D Rx in group B waits for the next PSCCH resource pool.

3.3. Time Repetition Pattern for Transmission

As mentioned above, SA contains resource location for data transmission, i.e., time and frequency. Location of frequency resources is explicitly recorded in SA, but location of time resources is implicitly recorded in SA by Time-Repetition Pattern for Transmission (T-RPT), which is expressed by 8-bit bitmap for indicating time resources.

In T-RPT, one bit indicates whether to transmit or not in one subframe (1 ms). Thus, one T-RPT indicates the subframes used to transmit during 8 ms and T-RPT repeats until PSSCH resource pool is finished. Therefore, through T-RPT, Tx and Rx can learn location of time resources. For example, we assume that the length of the period is 80 ms, i.e., the amount of time for PSCCH and PSSCH are 4 ms and 76 ms, respectively. Fig. 2 shows an example of T-RPT. Allocated T-RPT is 1 1 0 0 0 1 1 0 and the T-RPT repeats nine times completely until PSSCH resource pool is finished. After the nine repetitions, 4 ms remains. In that case, T-RPT is truncated by 4 ms, i.e., truncated T-RPT is 1 1 0 0, and then indicates subframes for 4 ms. Therefore, there are 38 data transmission times and nine Transport Blocks (TBs)\(^3\) are transmitted four times. The last TB is transmitted

\(^3\)TB corresponds to a MAC PDU, and the TB is passed from the MAC layer to PHY layer once per transmission time interval, i.e., 1 ms.
two times due to truncated T-RPT. According to 3GPP standard, the number of 1’s indicating the location of the subframe, which is allocated for transmission, is configurable, i.e., the number of 1’s is out of one, two, four, and eight. In this paper, we consider the number of 1’s is four.

4. System Model

In this section, we explain the target system model assuming that D2D UEs communicate with each other. We consider multicell scenarios with seven 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 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 know the own group information since the D2D UEs perform the D2D service authorization.

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 that resource allocation for SA follows mode 1, 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 [25]. As shown in Fig. 3, at the $\pm 180$ kHz from the center frequency, $(f_c)$, 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 of D2D Rxs, D2D Tx transmits signal with maximum power. 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 model to evaluate the impact of in-band emission in D2D communication.

5. Feedback Mechanism

We consider two philosophies for designing a feedback mechanism 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., two RBs are assigned to D2D Rxs and D2D Rxs transmit the feedback without additional signaling.

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. Therefore, when D2D Rxs transmit feedback only once, 24 D2D Rxs can transmit feedback using two RBs. In this paper, we use Zado-Chu sequences, which are known to have ideal auto-correlation property, with length 12. Since 3GPP considers the number of group members to be around 10 in general scenarios [25], the proposed feedback channel should be able to support all the group members.

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

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4Since one RB spans 12 subcarriers, a sequence of length 12 is used for one RB.
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 8, 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 4, 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 and the proposed rate adaptation algorithm is described in detail in Section 6.

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.

6. Groupcast Rate Adaptation Algorithm

On top of the proposed feedback channel, we propose a groupcast rate adaptation algorithm, called Fast and Robust Rate Adaptation (FaRRA) algorithm. FaRRA is an algorithm for D2D Rxs to effectively transmit feedback while trying to reduce in-band emission in the proposed feedback channel. In FaRRA 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. FaRRA 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 1 lists notations and parameters used in the pseudo codes for algorithms. Algorithm 1
Algorithm 1 Rx’s behavior of Faarra algorithm

Set:

1: $FI = 0$ \hspace{1cm} \triangleright \text{feedback sensing indicator}
2: $f_m = 0$ \hspace{1cm} \triangleright \text{supportable MCS level}
3: $m$ \hspace{1cm} \triangleright \text{ID of D2D Rx in consideration}

During $n$th SA transmission:

4: for $i \leftarrow 1, \ldots, N_{\text{time PSCCH}}$ do
5: \hspace{.5cm} for $j \leftarrow 1, \ldots, N_{\text{freq PSCCH}}$ do
6: \hspace{1cm} if $ID_m = ID_{i,j}$ then
7: \hspace{1.5cm} receive SA
8: \hspace{1cm} $M_n \leftarrow \text{MCS}_{i,j}$
9: \hspace{1cm} end if
10: \hspace{.5cm} end for
11: \hspace{.5cm} end for

During $n$th data transmission:

12: if receive SA then
13: \hspace{.5cm} receive data
14: \hspace{1cm} $\gamma \leftarrow E[\gamma_{\text{data}}]$ \hspace{1cm} // \text{data signal average SINR}
15: \hspace{1cm} while $\text{TBLER}(\gamma, f_m) \leq Th$ do
16: \hspace{1.5cm} $f_m = f_m + 1$
17: \hspace{1cm} end while
18: $FM_{n,m} \leftarrow f_m$
19: end if

During $n$th feedback transmission:

20: if $FM_{n,m} \geq M_n + 1$ then
21: \hspace{.5cm} monitor 1st feedback resource
22: \hspace{1cm} if sense feedback of receivers then
23: \hspace{1.5cm} $FI = 1$
24: \hspace{1cm} end if
25: \hspace{1cm} if $FI = 0$ then
26: \hspace{1.5cm} transmit feedback via 2nd resource
27: \hspace{1cm} end if
28: else
29: \hspace{1cm} if $FM_{n,m} < M_n + 1 \&\& FM_{n,m} \geq M_n$ then
30: \hspace{1.5cm} transmit feedback via 1st resource
31: else
32: \hspace{1.5cm} transmit feedback via 1st and 2nd resources
33: end if
34: end if

provides the behavior of D2D Rx with Faarra algorithm. The D2D Rx sets $FI$ and $f_m$ 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 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., $\gamma$, and the highest MCS level is fed back by the D2D Rx to D2D Tx.
Algorithm 2 Tx’s behavior of FaRRA algorithm

<table>
<thead>
<tr>
<th>Set:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1: $M_n$ $\triangleright$ MCS level used in $n$th period</td>
<td></td>
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<tr>
<td>2: $K$ $\triangleright$ the number of group members</td>
<td></td>
</tr>
<tr>
<td>3: $F_{rsc1} = \emptyset$ $\triangleright$ received feedback set</td>
<td></td>
</tr>
<tr>
<td>4: $F_{rsc2} = \emptyset$ $\triangleright$ received feedback set</td>
<td></td>
</tr>
<tr>
<td>During $n$th feedback period via 1st resource:</td>
<td></td>
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<tr>
<td>5: if receive feedback of $k$th Rx then</td>
<td></td>
</tr>
<tr>
<td>6: $F_{rsc1} \ni FM_{n,k}$</td>
<td></td>
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<tr>
<td>7: end if</td>
<td></td>
</tr>
<tr>
<td>During $n$th feedback period via 2nd resource:</td>
<td></td>
</tr>
<tr>
<td>8: if receive feedback of $k$th Rx then</td>
<td></td>
</tr>
<tr>
<td>9: $F_{rsc2} \ni FM_{n,k}$</td>
<td></td>
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<tr>
<td>10: end if</td>
<td></td>
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<tr>
<td>Rate adaptation for $(n+1)$th period:</td>
<td></td>
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<tr>
<td>11: if $F_{rsc1} = \emptyset$ then</td>
<td></td>
</tr>
<tr>
<td>12: if $|F_{rsc2}| = K$ then</td>
<td></td>
</tr>
<tr>
<td>13: $M_{n+1} \leftarrow \min(F_{rsc2})$</td>
<td></td>
</tr>
<tr>
<td>14: else</td>
<td></td>
</tr>
<tr>
<td>15: $M_{n+1} \leftarrow M_n + 1$</td>
<td></td>
</tr>
<tr>
<td>16: end if</td>
<td></td>
</tr>
<tr>
<td>17: else</td>
<td></td>
</tr>
<tr>
<td>18: if $F_{rsc2} = \emptyset$ then</td>
<td></td>
</tr>
<tr>
<td>19: $M_{n+1} \leftarrow M_n$</td>
<td></td>
</tr>
<tr>
<td>20: else</td>
<td></td>
</tr>
<tr>
<td>21: $F \leftarrow$ combining $F_{rsc1}$ and $F_{rsc2}$</td>
<td></td>
</tr>
<tr>
<td>22: $M_{n+1} \leftarrow \min(F)$</td>
<td></td>
</tr>
<tr>
<td>23: end if</td>
<td></td>
</tr>
<tr>
<td>24: end if</td>
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</table>

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 FaRRA algorithm, D2D Rxs, 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 Rxs, 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 successful 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 \( F_{\text{rsc}1st} \) and \( F_{\text{rsc}2nd} \) 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 \( F_{\text{rsc}1st} \). On the contrary, the received feedback via the second feedback resource is put into \( F_{\text{rsc}2nd} \) (lines 8–10).

During rate adaptation for the \((n + 1)\)th period (lines 11–24), D2D Tx first checks \( F_{\text{rsc}1st} \). If \( F_{\text{rsc}1st} \) is an empty set, the D2D Tx checks \( F_{\text{rsc}2nd} \). If the cardinality of \( F_{\text{rsc}2nd} \) is the same as the number of group members, the D2D Tx adapts the lowest MCS level based on \( F_{\text{rsc}2nd} \) (lines 11–13). Otherwise (lines 14–16), it means that the D2D Tx did not receive feedback from all D2D Rxs in the group. Therefore, in this case, the D2D Tx conservatively raises MCS level by one. If \( F_{\text{rsc}1st} \) is not an empty set, there exist demands for lowering or maintaining the current MCS level (lines 17–24). When \( F_{\text{rsc}2nd} \) is an empty set, the D2D Tx maintains the MCS level because there are only D2D Rxs, which want to maintain MCS level (lines 18–19). Otherwise, \( F_{\text{rsc}1st} \) and \( F_{\text{rsc}2nd} \) 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 \( F_{\text{rsc}1st} \) and \( F_{\text{rsc}2nd} \) (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 Rxs 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 on the received feedback. FaRRA 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 FaRRA 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. RO algorithm works in the same way as FaRRA algorithm during SA and data transmission. However, in RO algorithm, two turns, i.e., MCS level lowering turn and MCS level raising turn, are repeated alternately. In a MCS level lowering turn, only D2D Rxs, desiring to lower MCS level, transmit feedback and D2D Tx determines MCS level based on the received feedback. In a MCS level raising turn, both types of D2D Rxs, i.e., desiring to lower and desiring to maintain MCS level, transmit feedback and D2D Tx decreases or maintains MCS level if the D2D Tx receives feedback, which requests to decrease or maintain MCS level. If D2D Tx does not receive any feedback, the D2D Tx increases MCS level by one because all group members agree to raise MCS level.

FaRRA 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 FaRRA algorithm over in-band emission by comparing FaRRA algorithm with RO algorithm.

7. Feedback-Aided Recovery

In this section, we show that the our proposed feedback mechanism can enable packet recovery and propose a packet recovery scheme for D2D communications.

Data transmission without efficient encoding technique is difficult to efficiently retransmit packets due to the fact that 3GPP LTE-based D2D supports only groupcast. For example, if each group member requests to retransmit just one original packet, Tx might have to retransmit all original packets even though each member loses just one original packet.

We propose a method, which can solve the above mentioned difficulty caused by groupcast. We adopt Random Linear Network Coding (RLNC), which is a simple yet powerful encoding scheme [26]. RLNC can be also used without consultations between D2D Tx and D2D Rx since
the information used for decoding, i.e., coefficient vector information, is embedded in the header of each packet. Therefore, RLNC is suitable for LTE-based D2D. Through RLNC, Tx transmits encoded packets, which are linear combinations of a set of original packets with coefficients, which are randomly chosen from a finite field. Rx can recover the original packets from the received encoded packets if the number of linearly independent coefficient vectors among the received packets is equal to the number of original packets.

Fig. 6 illustrates how RLNC works. RLNC generates \( n \) encoded packets from \( k \) original packets to be transferred. Firstly, Fig. 6(a) shows encoding process of RLNC. The encoding process can be expressed as a product of matrices. \( A \) is an \( n \times k \) matrix consisting of coefficients of length \( q \) bits. We represent \( X \) as a \( k \times m \) original packet matrix by dividing an original packet of length \( d \) into \( m(=[d/q]) \) sub-packets. \( Y \) is an \( n \times m \) matrix resulting from the encoding, i.e., the encoding process can be expressed by \( AX = Y \).

Fig. 6(b) shows decoding process of RLNC. Tx transmits \( n \) encoded packets and Rx receives \( n' \) encoded packets due to channel errors or collisions, i.e., \( n' \) is less than or equal to \( n \). Even if packet losses occur in a transmission process, the original packets can be recovered if \( k \) encoded packets, which are linearly independent, are received, i.e., if the rank value of the coefficient matrix of the \( k \) encoded packets (\( \text{rank}(A') \)) is equal to the number of original packets (\( k \)), Rx can recover the original packets despite packet losses.

D2D Rxs, which want extra encoded packets, send the value obtained by subtracting the rank of the coefficient vectors of received linearly independent packets from the number of original packets via feedback. Then, D2D Tx determines the largest value based on the received feedback as the number of extra encoded packets to be transmitted.

As mentioned in Section 4, we consider the period for PSCCH and PSSCH is 80 ms, i.e., 4 ms is for PSCCH and the remaining time is for PSSCH and feedback transmission. Therefore, the number of transmissions is 36–40 and the number of original packets to be sent is 9–10 due to the blind retransmission and T-RPT.

When adopting the proposed feedback mechanism, the amount of time for PSSCH is decreased by 4 ms for feedback transmission, i.e., the amount of time for PSSCH is 72 ms. Therefore, by using the proposed feedback mechanism, the number of transmissions is 36. Therefore, we can generate 36 encoded packets by encoding 10 original packets to be sent. Extra encoded packet transmission is for the original packets, which are transmitted at the previous period. Therefore, the number of extra encoded packets (\( l \)) is less than or equal to 10. Then, the number of the remaining transmission opportunities is \( 36 - l \).
However, we not only transmit encoded packets, but also transmit original packets. Hence, we do not generate 36-l encoded packets, but transmit original packets and the remaining transmission opportunities are used for transmitting encoded packets. If all remaining transmission opportunities are used for generating encoded packets and Rx receives packets fewer than k, the Rx cannot recover any original packets. On the other hand, if a part of the remaining transmission opportunities is used for transmitting original packets and Rx receives packets fewer than k, Rx could avoid a situation where the Rx does not receive any packets. As shown in Fig. 7, when the period length is 80 ms, the number of transmissions is 36 and the transmission consists of three parts, i.e., extra encoded packet part, encoded packet part, and original packet part.

The number of original packets depends on the length of the period. Therefore, for period of 80 ms, the number of original packets is 10. The number of extra encoded packets (l) depends on the feedback requests. Tx receives feedback, which requests Tx to retransmit packets, and then determines the largest number of extra encoded packets based on the received feedback. Therefore, the range of l is from 0 to 10. The remaining transmission opportunities are used for transmitting encoded packets, i.e., the range of the number of encoded packets is from 16 to 26.

When the field size is large, the probability that Rx will obtain linearly independent combinations approaches one. However, the large field size causes overhead caused by attaching large coefficient vectors to encoded packets. Hence, it is important to select proper field size. While varying field size, we observe the above mentioned probability when the number of encoded packets is the smallest, i.e., 16 encoded packets due to extra encoded packets.

We confirm that the probability is close to one when the field size is larger than 4 bits. When MCS level 15 using 15 RBs, the overhead for attaching coefficients vector to encoded packet is 0.9%. Therefore, in this paper, we employ 4-bit coefficient field size to minimize the overhead while increasing the probability.

8. Performance Evaluation

In this section, we evaluate the impact of near-far problem over the proposed feedback channel and the performance of FaRRA algorithm. We also evaluate the performance of feedback-aided recovery on top of the proposed feedback mechanism. We follow the evaluation methodology in Annex A.2 of [25] 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.
8.1. Simulation Environments

Table 2 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 [27]. We also create shadowing following a log-normal distribution with standard deviation of 3 dB as specified in Clause A.2.1.2 of [25]. Pathloss is calculated using WINNER+B1 model [28]. Finally, in-band emission is also generated according to Clause A.2.1.5 of [25].

**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 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.

8.2. 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 Rxs, 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. 8 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.
8.3. Comparison of Rate Adaptation Algorithms

Now, we evaluate FaRRA algorithm in comparison with IE and RO algorithms. Fig. 9(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 Rxs, 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 Rxs has a severely negative impact on the reception of feedback by D2D Tx.

In case of FaRRA and RO algorithms, we observe that most MCS values are less than or equal to the highest achievable 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, FaRRA algorithm uses resources more efficiently because D2D Rx opportunistically transmits feedback requesting to raise MCS level.

Fig. 9(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. 9(b), FaRRA algorithm achieves higher goodput than the other algorithms. The red bars in Fig. 9(b) represent standard deviations. The standard deviation of FaRRA algorithm is slightly larger than that of RO algorithm because FaRRA algorithm is capable of supporting larger MCS level increase compared to RO algorithm. In summary, FaRRA 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.

8.4. Comparison of FaRRA Algorithm and Legacy Scheme

In this subsection, we compare FaRRA 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, 12, 18, or 24 during PSSCH. In case of the legacy scheme, 4 ms and 76 ms are for PSCCH and PSSCH, respectively. On the other hand, in FaRRA 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. 10 shows the goodput obtained by averaging the results from 100 simulation runs. We observe that FaRRA algorithm outperforms the legacy schemes while the legacy scheme with high MCS level tends to achieve higher average goodput. We also observe the 20th percentile goodput, representing the average of the bottom 20% of all goodput performances. We observe that the 20th 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 20th percentile goodput becomes clearer by evaluating the TBLER performance. Fig. 11 shows the result of TBLER for both FaRRA and the legacy schemes. We first observe that the TBLER of fixed MCS 24 is over 0.25, thus resulting in almost zero 20th percentile goodput. For fixed MCSs 6 and 12, although they have good TBLER performance, the 20th 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, FaRRA algorithm works properly by keeping the TBLER under the threshold, which is set to 0.1. That is, our simulation results demonstrate that FaRRA algorithm uses radio resources efficiently while keeping TBLER under the threshold.

8.5. Performance of Feedback-Aided Recovery Scheme

We compare performance of feedback-aided recovery with that of legacy scheme. We consider that radius of each cell is 300 m, and D2D Txs in both feedback-aided recovery scheme and legacy scheme use MCS level 15. The rest of the simulation environments follows Section 8.1. The legacy scheme refers to a scheme that uses blind retransmission to transmit without feedback mechanism. In feedback-aided recovery scheme, considering T-RPT and PSSCH period, i.e., 72 ms, D2D Tx transmits packets 36 times. On the other hand, in the legacy scheme, since feedback mechanism is not used, the PSSCH period is increased by 4 ms. Hence, there could be up to four more transmission opportunities depending on T-RPT, i.e., if allocated T-RPT is 1 1 1 1 0 0 0 0, D2D Tx transmits four more times. We consider T-RPTs that could be sent twice more than the feedback-aided recovery, so that the patterns have no significant effect on the results.

We first evaluate goodput performance of feedback-aided recovery. As shown in Fig. 12, Feedback-aided recovery achieves slightly higher average goodput than that of the legacy scheme. Requests for recovery are mostly made by D2D Rxs located at the edge of communication range. However,

---

5In D2D communications, cell radius is normally considered to be hundreds of meters [29, 30, 31]. In case of MCS level, we use MCS level 15 because we observe the best performance gain at MCS level 15. We also confirm that the choice of the two parameters has little effect on the trend of the performance.
since we deploy D2D Rxs uniformly, there are not many D2D Rxs, which request to recover. Thus, there is little difference in average performances. In order to better observe the performance gain due to recovery, we observe the 20th percentile goodput, representing the average of the bottom 20% of all goodput performances. In case of the 20th percentile goodput, feedback-aided recovery achieves 30% goodput performance gain. Through simulations, we confirm that the legacy scheme works quite robustly in terms of the average performance. However, considering that the 20th percentile performance is much lower than the average performance, D2D Rxs with the 20th percentile performance appear to be unable to receive packets frequently. Fig. 12 shows that feedback-aided recovery can effectively improve the 20th percentile performance as well as the average performance.

We also evaluate empirical CDF of file downloading time. The file downloading time is the number of periods used to download the file, completely. We assume that D2D Tx shares about 5 minutes of TED lecture video file6 with group members via D2D communication during 1,000 periods. As shown in Fig. 13, we observe the 20th percentile performances, representing CDF of the bottom 20% of all file downloading time performances. The average times of the lower 20% file downloading time of feedback-aided recovery and legacy scheme are 367.4 and 523.2, respectively, i.e., for D2D Rxs in the 20th percentile, the file downloading time can be reduced by about 150 periods with the feedback-aided recovery.

9. 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. On top of the proposed feedback mechanism, we propose FaRRA algorithm, a rate adaptation algorithm considering the impact of in-band emission. We also propose feedback-aided recovery method on the proposed feedback mechanism. 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 find that FaRRA algorithm is robust to in-band emission and uses radio resources more efficiently than the legacy schemes while keeping TBLER under the threshold. We also observe that feedback-aided recovery improves goodput performances of D2D Rxs with lower 20% performance and shortens file downloading time.

6The title of the TED lecture is “Don’t like clickbait? Don’t click” and the video file size is 31 MB.
References


[2] 3GPP TS 23.303, Proximity-based services (ProSe); stage 2 (ver. 12.0.0, Mar. 2015).


Table 1: Notations and parameters used in pseudo codes.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_{Ai,j} )</td>
<td>SA located at ( i )th subframe and ( j )th RB</td>
</tr>
<tr>
<td>( MCS_{Ai,j} )</td>
<td>MCS level within ( S_{Ai,j} )</td>
</tr>
<tr>
<td>( ID_{Ai,j} )</td>
<td>Group ID within ( S_{Ai,j} )</td>
</tr>
<tr>
<td>( ID_m )</td>
<td>Group ID of the ( m )th D2D UE</td>
</tr>
<tr>
<td>( M_n )</td>
<td>MCS level used in ( n )th period</td>
</tr>
<tr>
<td>( FM_{n,m} )</td>
<td>MCS level from the ( m )th UE in ( n )th feedback transmission</td>
</tr>
<tr>
<td>( N_{PSCCH} )</td>
<td>The number of subframes for PSCCH</td>
</tr>
<tr>
<td>( N_{freqPSCCH} )</td>
<td>The number of RBs at a given subframe for PSCCH</td>
</tr>
<tr>
<td>( FI )</td>
<td>Feedback sensing indicator</td>
</tr>
<tr>
<td>( \gamma_{data} )</td>
<td>SINR of received data</td>
</tr>
<tr>
<td>( fm )</td>
<td>Maximum supportable MCS level</td>
</tr>
<tr>
<td>( K )</td>
<td>The number of group members</td>
</tr>
<tr>
<td>( Th )</td>
<td>BLER threshold</td>
</tr>
<tr>
<td>( F_{rs1} )</td>
<td>Set of feedback successfully received via 1st feedback resource</td>
</tr>
<tr>
<td>( F_{rs2} )</td>
<td>Set of feedback successfully received via 2nd feedback resource</td>
</tr>
<tr>
<td>( F )</td>
<td>Set combined ( F_{rs1} ) and ( F_{rs2} )</td>
</tr>
</tbody>
</table>

[25] 3GPP TR 36.843, Study on LTE device to device proximity services; radio aspects (ver. 12.0.1, Mar. 2014).
[27] WINNER+ Deliverables, WINNER+ final channel models (D5.3, June 2010).
Figure 1: Behaviors of UEs in D2D communication: (a) SA transmission and reception and (b) Data transmission and reception.
Figure 2: An example of time repetition pattern for transmission.

Figure 3: Spectral mask of in-band emission.

Figure 4: An example of the proposed feedback mechanism for D2D communication.
Figure 5: D2D Rx behavior of FaRRA algorithm: (a) Rx to maintain MCS, (b) Rx to lower MCS, and (c) Rx to raise MCS.

Table 2: Simulation environments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td>System bandwidth</td>
<td>10 MHz (50 RBs)</td>
</tr>
<tr>
<td>Topology</td>
<td>Uniform distribution</td>
</tr>
<tr>
<td>Channel model</td>
<td>Fast fading + shadowing + pathloss + in-band emission [25]</td>
</tr>
<tr>
<td>The number of bits for ADC</td>
<td>12 bits</td>
</tr>
<tr>
<td>Transmission power</td>
<td>23 dBm</td>
</tr>
<tr>
<td>Noise figure</td>
<td>9 dB</td>
</tr>
<tr>
<td>Noise power</td>
<td>$-174$ dBm/Hz</td>
</tr>
</tbody>
</table>
Coefficient matrix $(n \times k)$
Original packet matrix $(k \times m)$
Encoded packet matrix $(n \times m)$

Original packet #1
Original packet #2
Original packet #k
Encoded packet #1
Encoded packet #2
Encoded packet #n

Finite field size (q bits)
Packet length (d bits)
Sub-packet length (q bits)

Figure 6: An example of random linear network coding $(AX = Y)$: (a) encoding and (b) decoding.

Figure 7: An example of composition of transmission.

Figure 8: Impacts of near-far problem.
Figure 9: Comparison of the algorithms: (a) MCS adaptation over time and (b) goodput performance of the worst channel Rx.

Figure 10: Overhead caused by feedback mechanism.

Figure 11: Transport block error rate.
Figure 12: Goodput performance of feedback-aided recovery.

Figure 13: Empirical CDF of file downloading time.