Distributed Resource Allocation Schemes for Out-of-Coverage D2D Communications

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***Abstract*—In many public safety scenarios, Device-to-Device (D2D) communication should be capable of handling out-of-coverage situations, ensuring that D2D devices can communicate directly without the aid of network infrastructure. While a number of resource allocation schemes for D2D communication in Long-Term Evolution (LTE) have been proposed, the majority consider only in-coverage scenarios that rely on a centralized controller to coordinate among D2D devices, and are unable to handle out-of-coverage communication. To address this issue, in this paper we investigate a set of distributed resource allocation schemes for out-of-coverage D2D group communication. To be specific, we first provide guidelines concerning how to allocate D2D resources based on Modulation and Coding Scheme (MCS), Physical Resource Block (PRB) size, and Time Resource Pattern (TRP) to meet the QoS requirements of applications. We then design three distributed resource allocation schemes that select PRBs in the resource pool and/or adjust the transmitting power based on the level of available information about the network environment. The first scheme, called the basic random allocation scheme, allows the transmitting User Equipment (UE) to randomly select resource blocks from the resource pool and transmit data at maximum power. The second scheme, which enhances the basic random scheme and is denoted as the Received Signal Strength (RSS)-based random allocation scheme, leverages RSS to reduce the power consumption of the transmitting UEs and interference to other groups. The third scheme proposed, designated the interference-aware allocation scheme, allows the transmitting UE to explore the interference experienced by receiving UEs within its D2D group and select resource blocks that interfere with the smallest number of UEs within the group. In doing so, the communication interference among transmitting UEs can be reduced, resulting in a higher probability of system coverage compared with the two random allocation schemes. To evaluate the designed distributed resource allocation schemes, we conduct extensive performance evaluation, validating their effectiveness in a variety of deployment scenarios.**

***Keywords*—D2D Communication, Out-of-Coverage, Distributed Resource Allocation.**

I. Introduction

To carry out public safety response and disaster recovery, emergency response communication is critical [1], [2], [3], [4], [5], [6]. When a large disaster occurs, network infrastructure will likely be overloaded, if not damaged and unavailable. To maintain continuous communications among first responders and victims, technologies to enable direct communication are paramount. Device-to-Device (D2D) communication, as one of several viable technologies to enable direct communication, is considered as a critically important technology in public safety research and development. With D2D, first responders and victims can directly communicate, enabling the sharing and collection of information, and providing situation awareness of public safety events. In these public safety scenarios, D2D communication needs to operate under out-of-coverage conditions, in which D2D devices need to communicate directly without the aid of network infrastructures [7], [8].

To carry out resource allocation in LTE-based D2D out-of-coverage situations, the following challenges need to be addressed. First, communication cannot rely on centralized controllers (base stations, etc.) to conduct resource allocation for D2D UEs. While a number of resource allocation schemes have been proposed, most consider only in-coverage D2D scenarios, where centralized controllers are required to coordinate resources. Additionally, these schemes often assume that complete knowledge of the Channel State Information (CSI) of communication and interference channels are available. Nonetheless, such an assumption is not applicable to the out-of-coverage D2D scenarios investigated in this paper. Second, in D2D group communication, as no physical layer feedback exists, little information regarding CSI is available. Thus, how to leverage the available information to improve system performance becomes a challenging issue. Third, UEs (including both transmitters and receivers) have less computation capabilities and are more sensitive to power consumption than larger and more heavily equipped base stations. Thus, existing complex resource allocation schemes become infeasible on UEs due to the limited computing and energy resources. Thus, the design of lightweight and distributed resource allocation schemes is essential to enable out-of-coverage D2D communications.

To address the issues presented thus far, in this paper we make the following concrete contributions.

- **Problem Formalization.** We formalize the resource allocation problem for out-of-coverage D2D communication in LTE-based networks. As the problem is a multi-dimensional issue, we consider several key factors together, including Modulation and Coding Scheme (MCS), Physical Resource Block (PRB) size, Time Resource Pattern (TRP) and transmitting power, to satisfy the quality of service (QoS) requirements for public safety applications. Once we complete the selection of these key factors, other important decisions include which PRBs in the pre-allocated resource pool should be used and what is the transmitting power level that should be utilized to transmit the signal so that the overall system coverage probability can be maximized.

- **Distributed Resource Allocation Schemes.** Based on the formalized problem, we design three distributed resource allocation schemes. Particularly, we first design a basic random allocation scheme, which allows the transmitting UE to randomly select resource blocks from the pre-configured resource pool. This scheme does not assume that the transmitting UE has any knowledge of the network. We then propose the Received Signal Strength (RSS)-based random resource allocation scheme that leverages the available information of the network so that the overall system performance can be improved. The RSS-based random scheme aims to reduce the power consumption of the transmitting UE by leveraging the D2D discovery service and identify the maximum path loss in the D2D group. Finally, we design the interference-aware allocation scheme, which allocates resources by avoiding interference of transmitting UEs. With this scheme, the transmitting UE collects information pertaining to the interference experienced by the receiving UEs in its group, and further selects resource blocks that are used by the least number of UEs. By doing this, the communication interference among transmitting UEs can be reduced so that the system coverage probability can be improved.
- **Extensive Evaluation.** We conduct extensive performance evaluation to show the effectiveness of our proposed schemes in allocating communication resources in out-of-coverage D2D communications with respect to system coverage probability, which is defined as the probability of average received Signal-to-Interference-plus-Noise Ratio (SINR) being larger than the minimum threshold required to successfully decode the information. We also measure the power consumption reduction of the RSS-based random scheme and investigate the tradeoffs of power savings and system coverage probability. Our findings show that the basic random scheme works effectively when the region is not dense (i.e., only a few communication groups exist in the region and the receivers in a group are closely located around the transmitter). When the geographic sizes of groups is small, power control could be used to reduce UE transmission losses with a marginal sacrifice in the coverage performance. When the region becomes more dense, the performance of the two random resource selection schemes deteriorate. Furthermore, the interference-aware scheme can significantly improve the coverage by mitigating interference among groups.

The remainder of this paper is organized as follows: In Section II, we provide a literature review of research relevant to our study. In Section III, we introduce the system model. In Section IV, we introduce the problem formalization, design rationale, and our designed distributed schemes in detail. In Section V, we present the performance evaluation results. Finally, we conclude the paper in Section VI.

II. Related Work

In this section, we review research works relevant to our study. D2D communication is essential for supporting public safety applications, as it enables continuous communication when network infrastructure is either damaged or overloaded [3]. D2D communication has the potential to not only improve communication resilience, but also improve spectrum efficiency, system throughput, energy efficiency, and system delay performance [9], [5], [6].

Generally speaking, D2D communication can be categorized as either in-coverage or out-of-coverage [9], [5], [6]. Particularly, in-coverage D2D means that D2D UEs are within the coverage range of network infrastructure, while out-coverage D2D means that D2D UEs are not in the coverage range of network infrastructure. When UEs are in-coverage, they may share the same radio resources with cellular services (underlay) [10], or use their dedicated resource pool for communication (overlay) [11]. For in-network D2D, traffic can either directly flow between two UEs or flow through the base station. In underlay cases, one challenge is how to minimize the impact of D2D on cellular networks and improve spectrum efficiency, while in overlay cases, challenges include how to choose proper resource pools for D2D so that resource use can be maximized. For out-of-coverage D2D, the primary challenge is how to effectively manage communication resources without the aid of base stations as centralized controllers or coordinators.

There is a body of research on D2D resource management, most of which are concerned with in-coverage D2D [5], [6], [9]. These existing D2D resource management efforts address coverage issues by designing a variety of resource allocation schemes to optimize certain performance metrics, including maximizing system throughput [12], [13], minimizing link outage probability [14], and maximizing overall energy efficiency [15], among others. The optimization objectives are also subject to a number of constraints, including transmission power, minimum QoS requirements, and physical resources, among others. D2D resource allocation also needs to consider a number of other factors, such as user traffic scheduling (i.e., how often the data will be transmitted), MCS selection, the size of physical resource blocks, transmission power, and mode selection to determine whether to utilize D2D or cellular communication modes (again, only for in-network scenarios). All of these factors are interconnected and jointly affect system performance. Thus, to simplify the problem, existing solutions often optimize one or several parameters of the entire parameter set. Commonly used techniques include integer/linear programming, convex optimization, mixed integer nonlinear programming, game theory approaches, and heuristic algorithm design, among others.

Most existing D2D research has focused on in-network underlay scenarios, ranging from the simple setup of one cellular UE and one D2D pair [10], to multiple D2D pairs and multiple cellular UEs [16], [17]. One focus is interference management, which includes issues such as how to minimize the impact of D2D communication on existing cellular services and how to manage cellular-to-D2D interference [16], [11]. For example, Su *et al.* [16] focused on D2D underlay in-band communication, studying how to control the interference from D2D UEs to the primary cellular UE by designing proper resource allocation and mode selection strategies. To solve the problem, a particle-swam optimization (PSO-MSRA)-based scheme was designed to maximize system throughput while guaranteeing the minimal rate requirement for all D2D users. Ye *et al.* adopted a game theory-based scheme and formulated the resource allocation in D2D underlay into a two-stage optimization problem [17]. While the proposed scheme might not find the optimum solution, it allows resources to be allocated in a distributed fashion. Notice that most of existing efforts on in-network are on underlay D2D, and perfect CSI is commonly assumed. There are some existing efforts on in-network overlay D2D as well. For instance, Lee *et al.* [11] studied D2D overlay resource allocation using graph-coloring to maximize the sum rate of D2D links. As a centralized solution, in their scheme, the eNodeB collects a list of high-interfering D2Ds and allocates resource to D2D transmitters.

As our work targets public safety scenarios, communication, and especially group communication, among public safety personnel need be maintained in the event of large-scale emergencies and disasters. Our research focuses on out-of-coverage D2D group communications, which have not been well explored. In our study, we take into account key factors that can be leveraged by a D2D UE locally, and design our solution to be practical, such that it could be implemented within the existing 3GPP framework with no or only slight modifications. We design three distributed schemes to conduct resource allocation for D2D communication to accommodate the special challenges associated with out-of-coverage communications.

III. System Model

In this section, we introduce the system model. In our study, we consider D2D group communication scenarios, in which a number of D2D nodes (i.e., UEs) that belong to different function groups are deployed in a geographical location and perform public safety missions. Within a group, there is one transmitter UE and multiple receiver UEs. The communications between transmitter UE and receiver UEs are performed directly through D2D communication links. Since UEs are not covered by network infrastructure, such as cellular networks, each UE has a pre-configured resource pool with K units in order to perform D2D communications in out-of-coverage scenarios. Without loss of the generality, we assume all UEs are configured with the same resource pool settings.

Figure 1 illustrates the network model, in which the deployment area is a circular area A with radius R. Within A, there are M groups uniformly randomly deployed, denoted as $G_1, G_2, \ldots, G_M$. Within a group G_i ($i \in [1, M]$), there is an active transmitter UE TXi and all other UEs within the same group are uniformly randomly located in a circular region that is centered on the transmitter UE_i with radius r.

Channel gain between transmitter TX_i ($i \in [1, M]$) and receiver UE_j is denoted as g_{ij}. When we compute the channel gain, path loss, large-scale shadowing, and small-scale fading are considered [18]. We also assume that the channel is a slow changing and semi-static. If we can collect coarse channel state information (e.g., CSI) using upper layer signaling (e.g., D2D discovery messages), such information could be used to guide resource allocation.

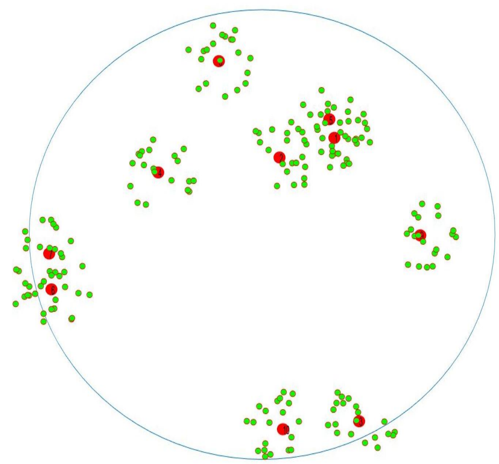

Fig. 1: Network Model

For transmitter TX_i (the transmitter in group i), we denote its transmission power as P_i. We assume all the transmitting groups are running the same application, such as mission critical voice. Resource allocation decisions include the selection of MCS, PRB size, TRP, transmission power, and PRB locations in the resource pool. We first allocate D2D resources by selecting MCS, PRB size, and TRP to meet QoS requirements of the application, such as requirements for throughput and delay. Based on the allocation scheme that we choose, we then divide the resource pool into a number of channels. Each channel occupies the same number of resources and a transmitter is using one channel.

Given M transmitters and K channels for D2D communication, we define the resource usage matrix U as

$$U_{M \times K} = \begin{bmatrix} 1 & 0 & 0 & \ldots & 0 \\ 0 & 1 & 0 & \ldots & 0 \\ \vdots & & \vdots & & \\ 0 & 0 & 0 & \ldots & 1 \end{bmatrix}$$

where $U_{i,j} =$

$$\begin{cases} 1, & \text{if TX } i \text{ uses channel } j \\ 0, & \text{if otherwise} \end{cases} \tag{1}$$

In our study, we consider an outdoor environment and adopt the 3GPP outdoor-to-outdoor (O2O) path loss model [19]. The line-of-sight (LOS) path loss PL_{LOS} and non-line-of-sight (NLOS) path loss PL_{NLOS} are defined as

$$\begin{aligned} PL_{LOS} = 40\log_{10}(d) + 7.56 - 17.3\log_{10}(h'_{BS}) \\ - 17.3\log_{10}(h'_{MS}) + 2.7\log_{10}(f_c) \\ + 20\log_{10}(f_C/f_{REF}), \end{aligned} \tag{2}$$

$$\begin{aligned} PL_{NLOS} = (44.9 - 6.55\log_{10}(h_{BS}))\log_{10}(d) + \\ 5.83\log_{10}(h_{BS}) + 16.33 + 26.16\log_{10}(f_C) - 5. \end{aligned} \tag{3}$$

Here, d is the distance between transmitter and receiver, and h'_{BS} and h'_{MS} are the effective heights for transmitter and receiver in meters, respectively, both of which are set to 0.8 m.

Also, f_c is the carrier frequency, set to 700 MHz, and the reference frequency f_{REF} is 2 GHz. For large-scale shadowing, log-normal shadowing with 7 dB standard deviation is used. For small-scale fading, Rayleigh fading is adopted. The probability of LOS is a function of distance following $P_{LOS} = min(18/d, 1)(1 - exp(-d/36)) + exp(-d/36)$.

IV. Proposed Schemes

In this section, we introduce our schemes in detail. Particularly, we first introduce coverage probability, which is used to evaluate our schemes, and present the optimization of coverage probability to motivate the design of distributed resource allocation. We then outline the problem definition and introduce the design rationale. Finally, we present our proposed schemes to allocate communication resources for out-of-coverage D2D.

A. Coverage Probability

In this study, we use coverage probability as the primary evaluation metric. Generally speaking, coverage probability is defined as the probability that the average received SINR is above the minimum threshold required to successfully decode the transmitted message. The coverage probability of a single transmitter and receiver link is a function of distance, and its expression is [18]

$$\frac{1}{\sqrt{\pi}\Gamma(m)} \int_{-\infty}^{+\infty} \exp(-x^2)\Gamma(m, \frac{m\gamma}{10^{\frac{\sqrt{2}\sigma_s x+\mu}{10}}})\, dx. \quad (4)$$

Here, $x = \frac{10log_{10}w-\mu}{\sqrt{2}\sigma}$ and $w = 10^{(\frac{\sqrt{2}\sigma_s x+\mu}{10})}$, σ_s is the standard deviation of the Log-normal shadowing, and μ is the received power after considering the path loss in dBm. $\Gamma(m)$ is the $\Gamma(.)$ function with an input of m, where $m = 1$ for Rayleigh fading. Also, γ is the decoding threshold that is dependent on the thermal noise, receiver noise figure, and SNR decoding threshold.

Considering interferences, the SINR of UEj in group i using channel k, denoted as $SINR_{j,k}$, can be computed as

$$SINR_{j,k} = \frac{P_{i,k}g_{i,j}}{\sum_{l=1,l\neq i}^{M} U_{l,k}P_{l,k}g_{l,j} + N}, \quad (5)$$

where $P_{i,k}$ is the transmitted power of transmitter UE i using channel k, $g_{i,j}$ is the channel gain between transmitter UE TX_i and receiver UE UE_j, M is the size of transmitter UEs, $U_{l,k}$ is the element of matrix defined in Equation (1), and N is the noise floor on the receiver, which includes thermal noise and noise introduced by the device. Notice that the channel gain includes the path loss, shadowing, and small scale fading.

For a given deployment (fixed transmitter and receiver locations), the path loss and shadowing for each link are fixed, we first compute the UE's average coverage probability over small-scale fading. For UE_j using channel k, its SINR can be written as

$$SINR_{j,k} = \gamma = \frac{g_0\omega_0}{\sum_{l=1,l\neq i}^{M} U_{l,k}g_l\omega_l + N}, \quad (6)$$

where ω_0 and ω_l are the local mean powers of the desired signal S_0 and interference signal S_l, i.e., the received powers after considering path loss and shadowing, which are fixed for a deployment. Also, g_0 and g_l are the power gain of the Rayleigh fading.

We define the coverage probability of UE_i as

$$\begin{aligned} P(\gamma \geq \beta|\omega) &= P(\frac{g_0\omega_0}{N + \sum_{l=1,l\neq i}^{M} U_{l,k}g_l\omega_l} \geq \beta|\omega), \\ &= P(\beta^{-1}g_0\omega_0 - \sum_{l=1,l\neq i}^{M} U_{l,k}g_l\omega_l \geq N|\omega), \\ &= P(S \geq \sum_{l=1,l\neq i}^{M} U_{l,k}g_l\omega_l + N|\omega). \end{aligned} \quad (7)$$

Here, β is the SNR threshold for successfully decoding the information from noisy communication channels in a given probability. Since g_0 and g_l are the power gains of the Rayleigh fading, the probability density function (PDF) of $S = \beta^{-1}g_0\omega_0$ is $f_S(s) = \frac{\beta}{\omega_0}\exp(\frac{-\beta s}{\omega_0})$ and let $y_l = U_{l,k}g_l\omega_l$, Equation (7) can be rewritten as:

$$\begin{aligned} P(\gamma \geq \beta|\omega) &= \int \cdots \int_{Y} \int_{N+\sum_{l=1,l\neq i}^{M} y_l}^{\infty} f_S(s)f_Y(y_1, \ldots, y_M)\, dsdY \\ &= \exp(-\beta_0 N) \int \cdots \int_{Y} exp(-\beta_0 \sum_{l=1,l\neq i}^{M} y_l) \\ &\quad f_Y(y_1, \ldots, y_M)\, dY \end{aligned} \quad (8)$$

Here, $\beta_0 = \frac{\beta}{\omega_0}$.

Since the UEs are deployed independently, y_i is an independent and identically distributed (i.i.d) random variable. Thus, we have

$$P(\gamma \geq \beta|\omega) = exp(-\beta_0 N) \prod_{l=1,l\neq i}^{M} \int_0^{\infty} exp(-\beta_0 y_l) f_Y(y_l) dy_l. \quad (9)$$

If the transmitter picks a channel randomly from a pre-allocated pool, we have PDF of $y_l = U_{l,k}g_l w_l$ as,

$$f_Y(y_l) = (1 - p_i)\delta(y_l) + p_i * \frac{1}{\omega_l}\exp(-\frac{y_l}{\omega_l}), \quad (10)$$

where $p_i = \frac{1}{N_{ch}}$ and N_{ch} is the total channel numbers.

After plugging in Equation (10), we have

$$\begin{aligned} P(\gamma \geq \beta|\omega) &= exp(-\beta_0 N) \prod_{l=1,l\neq i}^{M} \int_0^{\infty} exp(-\beta_0 y_l)((1 - \frac{1}{N_{ch}})\delta(y_l) \\ &\quad + \frac{1}{N_{ch}}\omega_l exp(-\frac{y_l}{\omega_l}))dy_l, \\ &= exp(-\beta_0 N) \prod_{l=1,l\neq i}^{M} \frac{1 + \beta_0\omega_l(1 - \frac{1}{N_{ch}})}{1 + \beta_0\omega_l}. \end{aligned} \quad (11)$$

Once we have the coverage probability for each UE with Equation (11), we can obtain the average UE's coverage probability in a fixed deployment. We then simulate the coverage probability over different deployments to obtain the average coverage probability for given system configurations, which vary by region size, number of groups, group region size, and others.

In a multi-group environment, we can choose matrix U such that the UE's average coverage probability can be maximized, i.e.

$$\max_{R}\sum_{i,k}P(S_{i,k}\geq t^{-1}+\sum_{l=1,l\neq i}^{M}U_{l,k}g_{l}w_{l}|w) \quad s.t.\sum_{j}U_{i,j}=1,\ P_{i}\leq P_{max} \tag{12}$$

Since the objective function is not a closed formula, directly finding for U matrix is very challenging. In addition, in out-of-coverage scenarios, without physical layer feedback and centralized control, it is difficult to collect sufficient information necessary to obtain the settings to maximize the average coverage probability. Thus, this motivates us to design distributed resource allocation schemes that are feasible in out-of-coverage D2D communications. In our study, we design an interference-aware scheduling scheme to select matrix U. Using the random channel selection scheme as a baseline, we investigate whether the coverage performance can be improved by selecting channels based on detected interference information. Once we have the channel allocation matrix U designed, the average coverage probability of UE i for a fixed deployment can be evaluated as:

$$\begin{aligned} P(\gamma_i\geq\beta|\omega) &= P(S\geq\sum_{l=1,l\neq i}^{M}U_{l,k}t_l+\tau^{-1}|\omega) \\ &= \int\cdots\int_{T}\int_{\tau^{-1}+\sum_{l=1,l\neq i}^{M}U_{l,k}t_l}^{\infty}f_S(s) \\ &\quad f_T(t_1,\ldots,t_M)\,dsdT, \\ &= \exp(-\beta_0 N)\int\cdots\int_{T} exp(-\beta_0\sum_{l=1}^{M}U_{l,k}t_l) \\ &\quad f_T(t_1)\ldots f_T(t_M)\,dT, \\ &= \exp(-\beta_0 N)\prod_{l=1,l\neq i,U_{l,k}=1}^{M}\frac{1}{1+\beta_0\omega_l}. \end{aligned} \tag{13}$$

Here, $f_T(t_l=g_l\omega_l)=\frac{1}{\omega_l}\exp(\frac{-t_l}{\omega_l})$.

Using Equations (11) and (13), we average out the small-scale fading, which can significantly reduce simulation time. To validate these two equations, we ran Monto Carlo simulations to simulate small-scale fading, and the comparison can be seen in Figure 2 and Figure 3. From both figures, we observe that the full-scale Monto Carlo simulations match well with the analytical results provided by Equations (10) and (13).

B. Design Rationale

Recall that, unlike in-coverage communication, in the out-of-coverage case, there is no base station acting as a central controller to allocate resources for each UE, and UEs need to schedule their resources autonomously. Thus, the problem we seek to address is, in the group communication scenario as described in Section III, how can transmitter UEs select resources with consideration for MCS, PRB size, and TRP to satisfy the QoS requirements of D2D communication, and how can UEs select transmitting power and the location of PRBs in the resource pool to improve system coverage probability. Notice that our focus is to improve the coverage probability so that the reliability requirements of public safety applications can be fulfilled. Other objectives (power consumption, system throughput, etc.) can be considered and extended in future extensions to this study.

According to the definition of coverage probability, UE j has coverage if $SINR_j > \beta$. Here, β is the SNR threshold in dB for UEj in order to achieve 10^{-2} Block Error Rate (BLER) after 4^{th} D2D transmissions. Notice that β is MCS dependent.

Depending on the availability of information on the deployment environment, we propose the following resource allocation schemes:

- *Basic Random Allocation Scheme*. In this scheme, each UE randomly selects resources from the resource pool in a uniform fashion based solely on its throughput requirement, without leveraging any knowledge, such as CSI. In this scheme, we do not conduct power control, such that the UE uses the maximum transmission power to send messages (what we consider the default configuration).
- *Received Signal Strength (RSS)-Based Random Allocation Scheme.* In this scheme, we intend to reduce UE power consumption by leveraging the D2D discovery service to identify the maximum path loss in the D2D group. Based on the maximum path loss in a group, the transmission power can be adjusted in the transmitting UEs, leading to reduction in power consumption, and potentially reduced interference with neighboring groups. Notice that UEs still randomly select the resources from the resource pool in a uniform fashion.
- *Interference-Aware Allocation Scheme.* In this scheme, the transmitter UE collects information on the interference experienced by the receiver UEs in its group, and selects the channels that can be detected by the least number of UEs in its group. By doing this, the communication interference among UEs can be reduced, such that the overall system coverage probability can be improved.

In the following, we describe our designed resource allocation schemes in detail.

C. Basic Random Allocation Scheme

In the basic random allocation scheme, to satisfy the throughput requirements of UEs, we need to select the proper combination of MCS, PRB size, and TRP. Notice that the resource pool size and transmission period length are pre-configured for all UEs to communicate outside cellular coverage. To illustrate this resource allocation scheme, we give an example. To support AMR-WB (Adaptive Multi-Rate - Wideband Speech Codec) voice applications, a throughput of 12.65 kbits/s is required, which means 253 bits for every 20 ms. After adding 3 bytes of RoHC (Robust Header Compression), LLC (Logical Link Control), and MAC (Media Access Control) headers, a transport block with a minimum size of 300 bits is required. If the period length is 40 ms, and 8

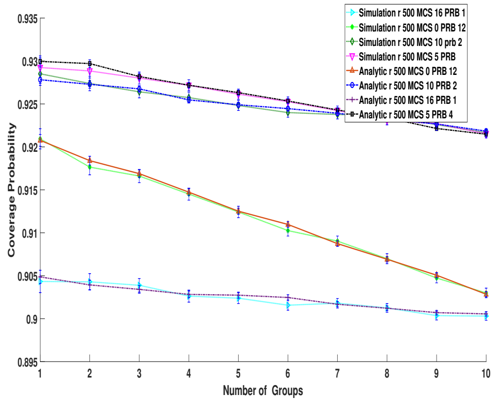

Fig. 2: Rayleigh Fading Simulation vs. Analytical (Eqn. (11)) for Random Channel Selection

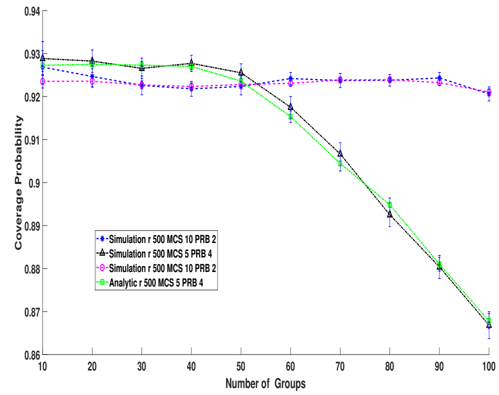

Fig. 3: Rayleigh Fading Simulation vs. Analytical (Eqn. (13)) for Interference Aware Scheme

MCS	PRB	Threshold (dB)	$10log_{10}PRB$	D
16	1	0.9	0	0.9
10	2	-3.8	3.01	-0.79
4	5	-7.5	6.99	-0.51
0	12	-11	10.79	-0.21
5	4	-6.6	6.02	-0.58

TABLE I: D values for different MCS and PRB combinations

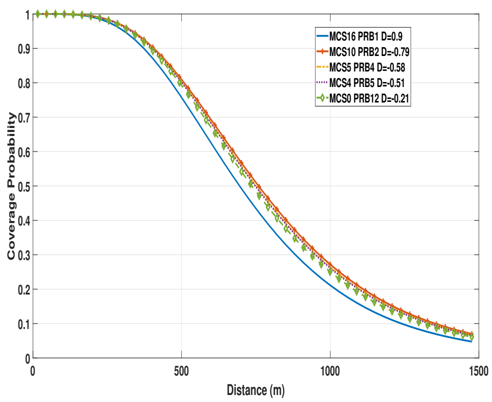

Fig. 4: Coverage Probability Comparison

subframes within the period are used for transmission, considering 4 retransmissions, a new transport block is transmitted every 20 ms.

Once the number of subframes to be transmitted in a transmission period is determined, we need to determine the transport block size to meet the QoS requirement (i.e., the amount of data to be transmitted in a subframe) of UEs. To satisfy the designated transport block size, we have several MCS and PRB size combinations. The problem is how to select the desired MCS and PRB pair among these combinations. As shown in our prior study [18], to successfully decode a transmitted message through a D2D link, a higher MCS value requires a higher SNR threshold. In contrast, if we choose a low MCS, we will use more PRBs, and noise floor will rise for the channel. The received signal strength should be greater than the receiver sensitivity to decode the signal successfully, and thus the maximum path loss that we can tolerate to achieve reliable communication is $P_{TX} - N - NF - SNR_{th}$ [18]. Here, N is the thermal noise floor and depends on the channel bandwidth, NF is the device noise figure, and SNR_{th} is the SNR to achieve 1 % BLER after the 4^{th} transmission.

Thus, with fixed transmitting power and noise figure, maximizing the path loss is equivalent to minimizing the sum of N and SNR_{th}. To maximize the propagation distance (i.e., maximizing the path loss that the receiver can tolerate), we consider the following objective: for each MCS and PRB size combination, we compute the utility function D_{max} as follows:

$$D_{max} = 10\log_{10} PRB + SNR_{th}. \tag{14}$$

We then pick the MCS and PRB size combination so that the smallest D value can be realized. We thus search through the MCS and PRB combinations that meet the throughput requirements. Table I illustrates some examples of D values. From the table, we can see that, by choosing the minimum D value, MCS 5 and PRB size 4 will be selected.

The average coverage probability of a link between one transmitter and one receiver for Rayleigh fading channel is computed by leveraging our prior work [18], and the results are shown in Figure 4. In the figure, we show the coverage probability for 5 different PRB and MCS combinations. Among these combinations, as a combination of MCS 16 and PRB 1 leads to the highest D value, the worst performance is achieved, while as a combination of MCS 10 and PRB 2 leads to the lowest D value, the best performance is achieved. A combination of MCS 5 and PRB 4 leads to the second best, resulting in the performance being close to the best. For the single D2D link, by picking the MCS and PRB combination with the lowest D value, we can maximize its coverage probability.

Notice that the aforementioned result is only for D2D links without interference from other transmitters. If each D2D transmitter uses this strategy, in a multi-group environment, it may not achieve the overall best system performance with respect to coverage probability. The resource allocation scheme using the smaller PRB can cause less interference to neighboring groups, which could outperform the best pair (e.g., MCS 5, PRB 4) with the increase of D2D groups in the region. Thus, depending on how dense the area is (i.e., the number of D2D groups packed in this area), a UE needs to give weight to a particular PRB size in order to achieve better system performance. With the pre-knowledge of the number of D2D groups in the deployed area, the UE can select the MCS and PRB pair accordingly so that the overall system performance can be improved. Algorithm 1 shows the procedure for selecting the MCS and PRB combination with the smallest D value in order to maximize coverage probability. As Algorithm 1 computes the MCS and PRB pair with the smallest D value by enumerating all combinations, its complexity is $O(n_{MCS} * n_{PRB})$, where n_{MCS} is the total number of MCSs and n_{PRB} is the total number of PRBs.

Algorithm 1: Algorithm for Selecting MCS and PRB Combination

Input: Throughput requirement and TRP settings
Output: The selected MCS and corresponding PRB
Compute minimal Transport Block (TB) Size = Throughput (bits/s)/Number of subframes transmitted Per Second
Check Table 7.1.7.2.1-1 [20] and list all the MCS and PRB combinations, whose corresponding TB sizes are equal to or above the minimal TB size
Compute utility function value D using Equation (14)
return The MCS and PRB combination that has the smallest D value

In the following, we introduce two other schemes that leverage available network information to improve the system performance.

D. RSS-based Random Scheme

We now introduce the RSS-based random resource allocation scheme, which adopts power control to reduce the energy consumption of the transmitter UEs and potentially reduces interference to neighboring groups. In the RSS-based random scheme, we leverage the D2D discovery service. There are two discovery modes: (i) *Model* A, and (ii) *Model* B. In Model A, the UE sends a discovery message autonomously, while in Model B, the UE is polled by neighboring nodes and sends the discovery response. Through Model B, the transmitter UE can send inquiries to its D2D group. Based on the SD-RSRP (Sidelink Discovery Reference Single Received Power) of the discovery response message, the path loss of UEs in the group can be estimated. Notice that RSRP is the average power received on the resource elements that carry the Demodulation Reference Signal (DMRS) of a decoded PSDCH (Physical Sidelink Discovery CHannel) signal. From the SD-RSRP and UE's transmitter power, the time averaged channel loss from the receiving UE in the group to the transmitter UE can be estimated. As D2D uses the LTE uplink spectrum for communication, D2D channels in both directions are reciprocal. Thus, we can estimate the channel loss from the transmitter UE to the receiver UE based on channel reciprocity.

Once the maximum channel loss in a group is available, the transmitter UE can use the same MCS and PRB as identified using the basic random allocation scheme, but instead of always transmitting using the maximum power, it may transmit with a reduced transmission power using the channel loss information. We assume network deployment is not fast-changing, and thus the CSI collected in the discovery process can be used to assist communication.

Power control can be conducted either open-loop or closed-loop. The open-loop control is to set the transmission power based on path loss and shadowing information, while the closed-loop control is used more often to accommodate the fast-fading effect. By controlling the transmitting power, UEs can not only save energy and improve battery life, but also reduce interference with other transmitting UEs in neighboring groups while preserving QoS of the UEs. Since D2D group communications do not have physical layer feedback and only coarse channel state information is available, we can only estimate path loss and shadowing effects from the discovery message from its group UEs, and the channel information is used to set transmitting power.

In this scheme, we introduce the compensation factor (CF), which denotes how much compensation we want for the channel loss (including both path loss and shadowing). The transmitted power after power control is

$$P_{tx} = \min((1-CF)P_{max} + CF \times PL_{max} + \text{noise floor}, P_{max}), \quad (15)$$

where the PL_{max} is the maximum channel loss of the radio link between transmitter UE and its group UEs. When CF is 1, P_{tx} is the minimum transmitting power to bring the received average power just above the noise floor. With the growth of CF, we can increase the transmitting power to have more margin and account for small-scale fading and the interference from other groups. Protocol 1 shows the detailed procedure for conducting power control.

Protocol 1 RSS-based Random Scheme

Inputs: Preselected MCS and PRB, and CF value
Output: UE transmitting power
Protocol:

1) Transmit UE sends discovery request using maximum power
2) UEs send back discovery responses after decoding the request using the maximum power
3) Transmit UE calculates the maximum channel loss experienced by its group and sets its transmit power using Equation (15)

Protocol 2 Interference Aware-Based Scheme

Inputs: Preselected MCS and PRB, and resource pool (channels)
Output: Which PRBs to select in the resource pool
Protocol:

1) Each UE monitors the channel that it can detect, and builds a list of channel with RSS greater than -105 dBm
2) Transmit UE sends discovery request using maximum power
3) UEs send back discovery responses with the channel list using the maximum power after decoding the request
4) Transmit UE sorts the interference channels by interference level, i.e. the number of group UEs that can detect this channel
5) Compute the channel that has the lowest level of interference

E. Interference-Aware Allocation Scheme

The resource allocation of the two aforementioned schemes are based on the random selection strategy, meaning that the transmitter UE randomly selects the PRB location uniformly from the resource pool. Notice that, in our study, we assume all transmitting UEs use just one channel, and each channel contains the same number of resource blocks. Thus, the problem becomes how to pick the channel for transmitter UEs. If a transmitter UE selects a channel randomly without knowledge of its environment, it may not achieve desirable system performance.

To consider interference, the transmitter UE first collects information about the interference experienced by the receiver UEs within its D2D group. This can be carried out by sending a discovery query message to nearby UEs. The UEs within the same group, after receiving the message, then piggy back the channels that it can detect (i.e., average RSS is above -105 dBm) using the discovery response message. When the information is collected, the transmitting UE will rank each channel by the number of group UEs that can detect that channel (i.e., the number of group members that are interfered by that channel). The channel detected by the least number of transmitters will be selected by the transmitter UE. If there are multiple channels that could satisfy the requirements, we will select the channel that has been used most recently. If no such information available, we will randomly pick one from the multiple channels. For example, if two transmitters can be detected by the same receiver, these two transmitters become interferers to each other, and we should try to put these two on different channels so that interference between them can be avoided. Thus, if a transmitter's total number of interference channels is less than the size of the channel pool, the transmitter can use one of the unused channels to transmit. If the transmitter is located within a much more dense area, and all the channels have been used by all neighbor transmitters, the channel detected by the minimum number of UEs in its group will be picked. Protocol 2 shows the detailed procedure for conducting the channel selection with the least interference.

V. Performance Evaluation

In this section, we present our performance evaluation. In particular, we first introduce the evaluation methodology and provide evaluation results.

A. Methodology

To evaluate the performance of the D2D group communication system, we consider coverage probability, defined in Section IV, as the key metric. To evaluate the power saving performance, we measure the power saved in the transmitting UE as the ratio of the power usage from all transmitter UEs transmitting at maximum power to the power usage when the power control scheme is in place, the results of which are presented in units of dB.

To simulate a group communication scenario, a number of UE groups are deployed in a circular region with radius 3000 m. Within each group, 20 receiver UEs are deployed within a small circle around the transmitter UE. We evaluate the performance by varying the number of groups in the region in order to simulate a region with different levels of density. We also evaluate the impact of group size on performance by varying the closeness of the receivers to the transmitters. We assume all the transmitter UEs have full buffers so that the transmission is continuous. For fixed locations of transmitters and receivers, we generate log-normal random variables to simulate the shadowing effect of the channel between each transmitter and receiver pair. With the deployment and shadowing information, we can compute the area mean power of a receiver and use Equations (10) and (13) in Section IV-A to compute the average coverage probability of a deployment, and we can simulate hundreds of deployments to obtain average performance.

B. Results

1) Basic Random Allocation Scheme: Figure 5 illustrates the coverage probability vs. the number of D2D groups in a range of [1, 10]. Figure 6 illustrates the coverage probability vs. the number D2D groups in a range of [10, 100]. From both figures, we can make the following observations. First, when the number of groups increases, the coverage probability reduces due to the increase in interference. When UEs in a group are geographically close to each other (i.e., r is 300 m), receiving UEs have higher desired signal power and experience less interference from other transmitter groups, such that the average coverage probability is better than for UEs in more dispersed groups (i.e., r is 500 m). For just a single D2D group, the combination of MCS 5 and PRB 4 achieves the best coverage with a small margin over MCS 10 and RPB 2 (due to the smallest D value). With the increase in number of D2D groups, MCS 10 and PRB 2 soon outperform MCS 5 and PRB 4.

Additionally, with PRB 12, since it uses MCS 0, which requires the lowest SNR to decode the signal, when there is only 1 group, it performs better than MCS 16 and PRB 1. However, when the number of UE groups in a region reaches a certain level, the interference becomes a problem. When this

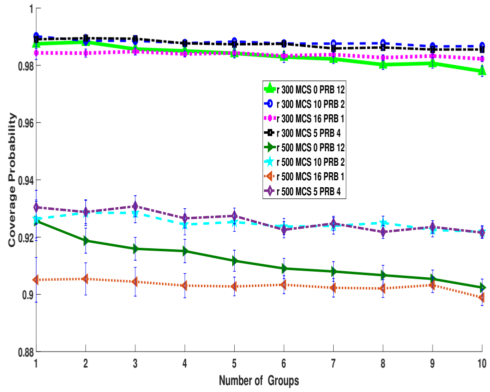

Fig. 5: Basic Random Scheme (R = 3000 m, r = 100 m, 500 m, Group=[1,10])

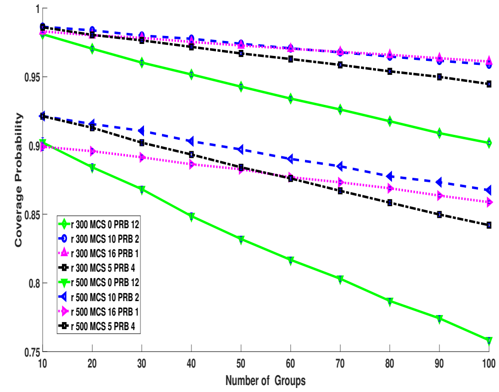

Fig. 6: Basic Random Scheme (R = 3000 m, r =300 m, 500 m, Group=[10,100])

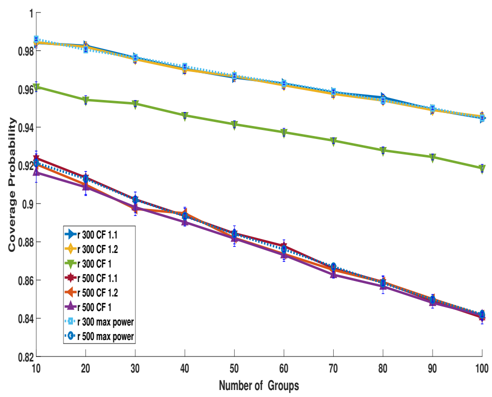

Fig. 7: Coverage Probability of RSS-based Random Scheme (MCS=10, PRB=2)

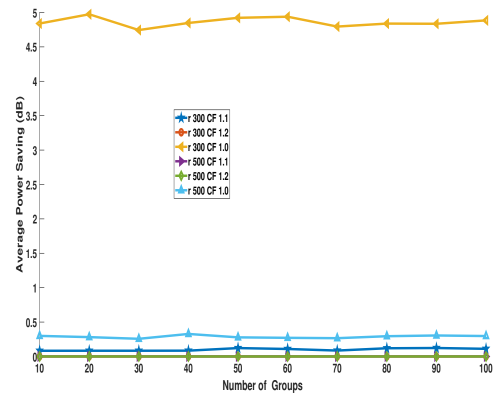

Fig. 8: Power Saving of RSS-Based Random Scheme (MCS = 10, PRB = 2)

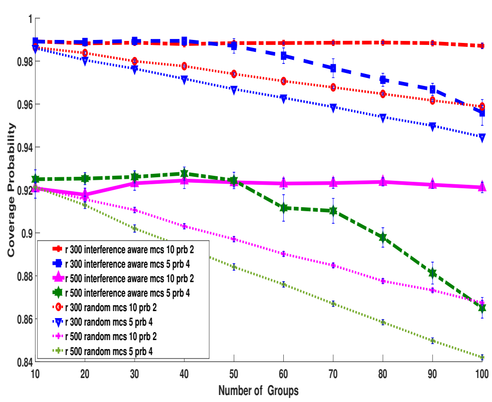

Fig. 9: Coverage Probability of Interference Aware Allocation Scheme (R = 3000 m, r = 300 m, 500 m)

occurs, MCS 12 starts having better coverage probability than MCS 0. This is because, with the fixed resource block size, more channels can be divided for PRB 12 than for PRB 1, leading to a lower chance of collision in the frequency domain. In general, when the system is dense, or more transmitters are deployed in a given region, the resource allocation schemes that using less resources have a performance advantage. Notice that, in the basic random scheme, we do not take into account the interference from different groups. This is the decision made by the transmitter UE itself. If each D2D UE uses this scheme, it may not achieve the overall best average coverage probability. Thus, depending on how dense the area is (i.e., how many D2D groups are packed into the deployment area), the UE more heavily weights a smaller PRB size in order to achieve better coverage.

2) RSS-Based Random Allocation Scheme: Figure 7 illustrates the average coverage probability vs. the number of groups (which varies from 10 to 100), where power control is used with different values of CF. Notice that, when CF is 1, we have enough transmitting power to compensate for the average channel loss due to path loss and shadowing. When CF is greater than 1, we overcompensate for the average channel loss to accommodate for the small-scale fading and the interference from other transmitters. Figure 8 illustrates the average power savings in transmitter UEs as the number of groups varies from 10 to 100, and the system implements the RSS-based random scheme. For both figures, the PRB size is set to 2 and the MCS is fixed at 10.

From these two figures, we can observe that, when r is small (r is 300 m) and CF is 1, UEs can save around 5 dB in transmitting power on average, with about a 2 % drop in the coverage probability. However, when r becomes large (r is 500 m), to compensate for the largest channel loss in a D2D group, the transmitting power is close to the maximum transmitting power and the power savings become insignificant (around 0.3 dB). As a consequence, the coverage probability is comparable to that of the maximum transmitting power. When CF is 1.1 or 1.2, there is almost no power savings, meaning that the transmitting UEs are approximately using the maximum transmitting power. Based on our evaluation results, we confirm that there are tradeoffs between coverage probability and power saving improvements, meaning that greater power savings results in a sacrifice in the form of lower coverage probability.

3) Interference-Aware Allocation Scheme: Figure 9 shows the average coverage probability for two different UE groups with receive UE deployment distances of r=300 m and r = 500 m. We also demonstrate the performance of two MCS configurations (i.e., MCS 10 and MCS 5). We can observe that, when the UEs are closer together, the coverage performance is good, even with a random channel selection. When MCS is 10, since it uses less PRBs, radio resources can be divided into more channels. With the interference-aware scheme, when there are up to 100 groups in the circular region of radius of 3000 m, the interference can be mitigated well and the average coverage probability remains flat. However, when MCS is 5, since it uses double the size of PRB compared to MCS 10, the number of channel divisions that it can allocate is only half. Thus, we can observe that the coverage probability for MCS 5 starts dropping when the number of groups reaches approximately 50, since there are not enough channels to avoid interference. Thus, using neighboring D2D group information, we confirm that coverage probability can be significantly improved, especially when region is dense, assuming appropriate channel selection.

VI. Final Remarks

In this paper, we have addressed the resource allocation issue of out-of-coverage D2D scenarios for public safety communications and investigated three distributed resource allocation schemes. To be specific, we first showed how UEs could schedule resources based on the throughput requirements of applications and maximize transmission coverage. We then investigated how to select the physical block size in the resource pool once the decision is made on MCS and PRB size. To do so, we proposed three distributed resource allocation schemes. In the basic random allocation scheme, no D2D deployment information is relied upon to select resources. In the RSS-based random allocation scheme, power control is used to reduce the energy consumption of the transmitting UEs. In addition to the random allocation schemes, we propose an inference-aware scheme that allows transmitter UEs to collect interference information from nearby D2D groups. By using such information, the interference among UEs can be reduced, leading to performance improvement. We conducted an extensive performance evaluation to validate the effectiveness of our proposed schemes. Our findings show that the basic random allocation scheme works effectively when the region is not dense, the power control scheme is capable of reducing UE transmission power with only a small sacrifice in coverage performance when receiver UEs belong to a group are deployed close to the transmitter, and the interference-aware scheme can significantly improve coverage by mitigating interference among groups.

References

[1] R. A. Rouil, A. I. Manzanares, M. R. Souryal, C. A. Gentile, D. W. Griffith, and N. T. Golmie, "Modeling a nationwide public safety broadband network," *IEEE Transactions on Vehicular Technology*, vol. 8, no. 2, pp. 83–91, 2013.

[2] G. Baldini, S. Karanasios, D. Allen, and F. Vergari, "Survey of wireless communication technologies for public safety," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 2, pp. 619–641, 2014.

[3] G. Fodor, S. Parkvall, S. Sorrentino, P. Wallentin, Q. Lu, and N. Brahmi, "Device-to-device communications for national security and public safety," *IEEE Access*, vol. 2, pp. 1510 – 1520, 2014.

[4] A. Kumbhar, F. Koohifar, . Gven, and B. Mueller, "A survey on legacy and emerging technologies for public safety communications," *IEEE Communications Surveys Tutorials*, vol. 19, no. 1, pp. 97–124, Firstquarter 2017.

[5] W. Yu, H. Xu, J. Nguyen, E. Blasch, A. Hematian, and W. Gao, "Survey of public safety communications: User-side and network-side solutions and future directions," *IEEE Access*, vol. 6, pp. 70 397–70 425, 2018.

[6] A. Jarwan, A. Sabbah, M. Ibnkahla, and O. Issa, "LTE-based public safety networks: A survey," *IEEE Communications Surveys Tutorials*, pp. 1–1, 2019.

[7] S. Lien, C. Chien, F. Tseng, and T. Ho, "3GPP device-to-device communications for beyond 4G cellular networks," *IEEE Communications Magazine*, vol. 54, no. 3, pp. 29–35, March 2016.

[8] S. Gamboa, F. J. Cintron, D. Griffith, and R. Rouil, "Adaptive synchronization reference selection for out-of-coverage proximity services," in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Oct 2017, pp. 1–7.

[9] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Communications Surveys Tutorials*, vol. 16, no. 4, pp. 1801–1819, Fourthquarter 2014.

[10] Y. Pei and Y. Liang, "Resource allocation for device-to-device communication overlaying two-way cellular networks," in *2013 IEEE Wireless Communications and Networking Conference (WCNC)*, April 2013, pp. 3346–3351.

[11] C. Lee, S. Oh, and J. Shin, "Resource allocation for device-to-device communications based on graph-coloring," in *2015 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS)*, Nov 2015.

[12] T. Peng, Q. Lu, H. Wang, S. Xu, and W. Wang, "Interference avoidance mechanisms in the hybrid cellular and device-to-device systems," in *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, Sep. 2009, pp. 617–621.

[13] S. Xu, H. Wang, T. Chen, Q. Huang, and T. Peng, "Effective interference cancellation scheme for device-to-device communication underlaying cellular networks," in *2010 IEEE 72nd Vehicular Technology Conference - Fall*, Sep. 2010, pp. 1–5.

[14] K. Vanganuru, S. Ferrante, and G. Sternberg, "System capacity and coverage of a cellular network with D2D mobile relays," in *MILCOM 2012 - 2012 IEEE Military Communications Conference*, Oct 2012, pp. 1–6.

[15] M. Jung, K. Hwang, and S. Choi, "Joint mode selection and power allocation scheme for power-efficient device-to-device (D2D) communication," in *2012 IEEE 75th Vehicular Technology Conference (VTC Spring)*, May 2012, pp. 1–5.

[16] L. Su, Y. Ji, P. Wang, and F. Liu, "Resource allocation using particle swarm optimization for D2D communication underlay of cellular networks," in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, April 2013.

[17] Q. Ye, M. Al-Shalash, C. Caramanis, and J. G. Andrews, "Distributed resource allocation in device-to-device enhanced cellular networks," *IEEE Transactions on Communications*, vol. 63, no. 2, pp. 441–454, Feb 2015.

[18] J. Wang and R. Rouil, "Assessing coverage and throughput for D2D communication," in *IEEE International Conference on Communication (ICC)*, May 2018.

[19] 3GPP, "Technical Specification Group Radio Access Network; Study on LTE Device to Device Proximity Services; Radio Aspects v.12.0.1 ," 3rd Generation Partnership Project (3GPP), TR 36.843, 2014.

[20] ——, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures,; v.13.2.0," 3rd Generation Partnership Project (3GPP), TS 36.213, 2016.