Soft Frequency Reuse-Based Resource Allocation for D2D Communications Using Both Licensed and Unlicensed Bands

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***Abstract*—To realize D2D communications, several challenging issues such as the device discovery, spectrum resource allocation, interference management, power control, and communication security remain to be studied. In this paper, we intend to design a resource allocation algorithm which is based on the soft frequency reuse (SFR) scheme, adopts power control, alleviates interference, and uses both the licensed and unlicensed bands for D2D communications. Simulation results demonstrate that the proposed resource allocation algorithm achieves much better performance in terms of system capacity and blocking rate, compared with the conventional allocation scheme that purely uses the licensed band and does not support D2D.**

***Index Terms*—Device-to-device (D2D) communications, interference management, resource allocation, soft frequency reuse (SFR), unlicensed band, wireless cellular networks.**

I. Introduction

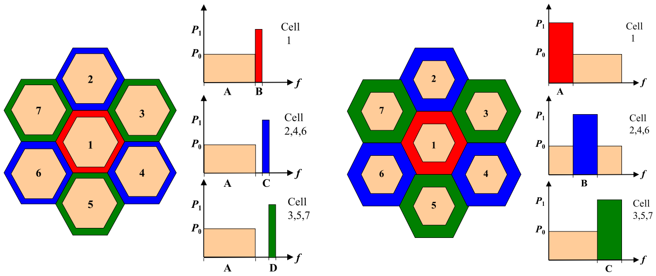
The high data rate of 5G networks can strongly realize Internet of things (IoTs) and smart cities. However, IoTs and smart cities may generate large volume of data and overload the 5G networks because of the limited spectrum resources. To solve this problem, device-to-device (D2D) communications [1]–[3] have been proposed recently. In D2D communications, two devices directly communicate with each other without using the base station (BS) for relaying. Hence, D2D communications yield several advantages [2]–[5] such as offloading the 5G networks, extending the network coverage, increasing the bit rates, and reducing network latency and power consumption of UEs. However, several challenging issues such as the device discovery, spectrum resource allocation, interference management, power control, and communication security, exist in D2D communications [1], [3], [4]. One of the key issues in D2D communications is the resource allocation. Therefore, several works [5]–[9] have proposed different resource allocation algorithms for D2D links.

Resource allocation for D2D communications can be centralized or distributed. The centralized resource allocation scheme in which the BS is assumed to have the global network information and thus can optimize the resource allocation has been extensively studied, e.g., in [5], [6]. The work [5] proposed the resource allocation scheme that schedules multiple D2D links to reuse the same resource block under feasible access pattern constraints. The study [6] proposed a joint power control and resource scheduling scheme for D2D communications to increase both the throughput and users' fairness. However, in future networks assuming that the BS has the global network information is unrealistic, especially in a time-varying environment. Hence, the distributed resource allocation scheme which may not achieve the optimal resource allocation was proposed [7]. The authors in [7] used uncoupled stochastic learning algorithm (SLA) to distributedly learn the resource and the transmit power level and solved this problem based on a Stackelberg game with pricing model.

Real-time D2D communications are important for some applications such as intelligent transportation, IoTs, etc. Thus, the work [8] proposed a resource allocation and power control algorithm to maximize the capacity of all D2D users while guaranteeing the QoS of users. In [9], the authors investigated the resource allocation for real-time D2D communications aiming to maximize the total utility of packets while meeting their deadlines.

To increase the spectral efficiency of LTE-A networks, the single carrier OFDMA (SC-OFDMA) is strongly recommended. However, SC-OFDMA imposes severe interference at cell-edge region and degrades system performance. To solve this interference problem, the fractional frequency reuse (FFR) and soft frequency reuse (SFR) were proposed for SC-OFDMA cellular networks, as shown in Fig. 1 [10]. Several resource allocation schemes based on the FFR or SFR have been proposed [10], [11]. The paper [11] designed three resource allocation schemes for D2D links under the cellular network employing FFR or SFR. Numerical results show that these schemes achieve less interference on D2D links while satisfying the QoS requirement of cellular users.

To further increase the system capacity of 5G networks, unlicensed bands can also be considered for use in D2D communications [3], [12]. Unlicensed band D2D protocols such as Wi-Fi Direct and Bluetooth already exist on the market. Therefore, there is no difficulty in using unlicensed bands for D2D communications. This paper aims to design a resource allocation algorithm for D2D communications using licensed and unlicensed bands under an SFR-based network.



(a) FFR. (b) SFR.

Fig. 1: Illustration of FFR and SFR [10].

The rest of this paper is organized as follows. Section II describes the proposed resource allocation scheme. Section III conducts simulations to evaluate the performance of the proposed resource allocation scheme. Finally, the concluding remarks are given in Section IV.

II. Proposed Resource Allocation Scheme

In the proposed resource allocation algorithm, D2D links are classified into two types: short-range D2D (SRD) and long-range D2D (LRD). When the distance between the two UEs of a D2D link is less than d, the D2D link is categorized as the SRD. If the distance between the two UEs of a D2D link ranges from d to D ($d < D$), the D2D link is categorized as the LRD. Two UEs more than D apart cannot initiate D2D communications and are classified as regular cellular users (CUs). Spectrum allocation for D2D links includes three modes: dedicated mode, reused mode, and unlicensed mode. In the dedicated mode, D2D links use unique spectrum resources of the licensed band. In the reused mode, D2D links reuse the spectrum resources, which have been allocated to D2D links, of the licensed band. While in the unlicensed mode, D2D links share the unlicensed band. Notably, for D2D links, the reused mode has the highest allocation priority while the unlicensed mode has the lowest one. CUs are always allocated resources using the dedicated mode or unlicensed mode.

The proposed resource allocation algorithm is based on the SFR [10], [11] which can effectively alleviate the inter-cell interference. In SFR, all UEs are classified as cell-center or cell-edge UEs according to their SNRs or distances to the base station. In this paper, the case that the signal strength attenuation is only due to the free space path loss is considered. Hence, the UEs located within the region of a predefined circle whose center is the base station and radius is less than r are classified as cell-center UEs, while the others outside the predefined circle are named cell-edge UEs. In each cell, the proposed resource allocation algorithm which is executed according to the types (SRD or LRD) and locations (cell-center or cell-edge) of D2D links is described step by step as follows.

For SRD Links:

1a) For an SRD link x, if both the distance between the receiver of SRD link x and the transmitter of any SRD link y ($y \neq x$) and the distance between the transmitter of SRD link x and the receiver of any SRD link y ($y \neq x$) are larger than d, then the reused mode is used for the SRD link x (using the same spectrum resources as SRD link y). Otherwise, go to step 1b.

1b) If the distance between the receiver of SRD link x and the transmitter of any LRD link y ($y \neq x$) is larger than D and the distance between the transmitter of SRD link x and the receiver of any LRD link y ($y \neq x$) is larger than d, then the reused mode is used for the SRD link x (using the same spectrum resources as LRD link y). Otherwise, go to step 1c.

1c) If the remaining spectrum resources of the licensed band is enough for SRD link x, then the dedicated mode is used. Otherwise, go to step 1d.

1d) If the number of sessions using the unlicensed band is less than a predefined number N, then the unlicensed mode is used. Otherwise, the SRD link x is rejected.

For LRD Links:

2a) For an LRD link x, if the distance between the receiver of LRD link x and the transmitter of any SRD link y ($y \neq x$) is larger than d and the distance between the transmitter of LRD link x and the receiver of any SRD link y ($y \neq x$) is larger than D, then the reused mode is used for the LRD link x (using the same spectrum resources as SRD link y). Otherwise, go to step 2b.

2b) If both the distance between the receiver of LRD link x and the transmitter of any LRD link y ($y \neq x$) and the distance between the transmitter of LRD link x and the receiver of any LRD link y ($y \neq x$) are larger than D, then the reused mode is used for the LRD link x (using the same spectrum resources as LRD link y). Otherwise, go to step 2c.

2c) If the transmitter of LRD link x is located in the cell-center region and the remaining spectrum resources of the licensed band is enough for LRD link x, then the dedicated mode is used. If the transmitter of LRD link x is located in the cell-edge region and the remaining spectrum resources of the licensed cell-edge band is enough for LRD link x, then the dedicated mode is also used. Otherwise, go to step 2d.

2d) If the number of sessions using the unlicensed band is less than N, then the unlicensed mode is used. Otherwise, the LRD link x is rejected.

Notably, in the proposed algorithm if the signal coverage of a D2D link exceeds the cell range, only the cell-edge band can be reused or allocated in order to avoid inter-cell interference.

III. Numerical Results

In this section, we employ simulations to evaluate the performance of the proposed resource allocation algorithm. The simulation program is developed by ourselves using the C++ Builder. The radius of the considered cell is 400m. The maximum distances d (D) between the transmitter and receiver of an SRD (LRD) link is 100m (200m). The maximum number

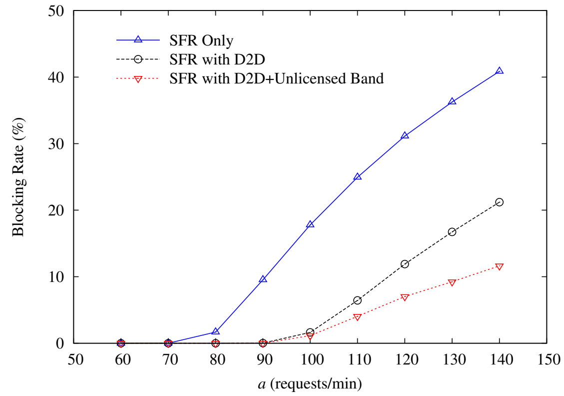


Fig. 2: Comparison of blocking rates.

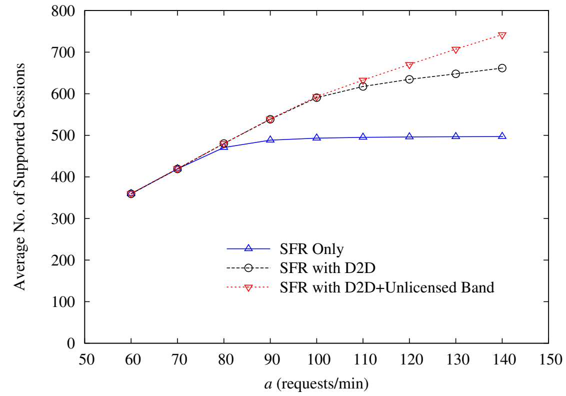


Fig. 3: Comparison of average number of supported sessions.

N of supported sessions in the unlicensed band is assumed to be 100. All UEs are uniformly distributed over the considered cell, i.e., follows the Poisson point process. The area ratio of cell-center region to cell-edge region is set to 0.7, i.e., r = 334.7m. The arrival process of real-time sessions of UEs follows the Poisson process with rate a, and 20% of real-time sessions can use D2D communications. We assume that each CU or D2D link has at most one real-time session at any time. The service time of each session is an exponential random variable with mean service time 360s. The blocking rate and average number of supported sessions of different resource allocation schemes, including SFR only, SFR with D2D, and SFR with D2D+unlicensed band (the proposed algorithm), are evaluated and compared. In the SFR only scheme, no reused and unlicensed modes are used. While in the SFR with D2D, no unlicensed mode is used.

Figures 2 and 3 plot the blocking rate and average number of supported sessions under different resource allocation schemes. Obviously, the proposed algorithm achieves the best performance, in terms of the blocking rate and average number of supported sessions. According to the simulation results, one can observe that D2D can significantly improve the system performance, compared with the SFR only scheme. Additionally, using the unlicensed band for wireless cellular networks can further enhance the system performance. All numerical results demonstrate that the proposed resource allocation algorithm for D2D communications is outstanding.

IV. Conclusions

In this work, we propose a resource allocation algorithm, which considers SFR and unlicensed band, for wireless cellular networks supporting D2D communications. D2D links first consider the reused mode and second choose the dedicated mode. If the reused and dedicated modes are not possible, then the unlicensed mode is considered. The blocking rate and average number of supported sessions, which have a constant average data rate requirement, of the proposed resource allocation algorithm are evaluated by simulations. Simulation results demonstrate that D2D communications significantly improve the system performance. Additionally, adopting the unlicensed band can further increase the system performance. Hence, the proposed resource allocation algorithm based on SFR and using unlicensed band is an outstanding design.

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