Vehicular Communications 26 (2020) 100282

Contents lists available at ScienceDirect

Vehicular Communications

www.elsevier.com/locate/vehcom

Cooperative resource management for C-V2I communications in a dense urban environment ☆

Umair Ahmad Mughal, Jiao Xiao, Ishtiaq Ahmad, KyungHi Chang *

Department of Electrical and Computer Engineering, Inha University, Incheon, 22212, Republic of Korea

A R T I C L E   I N F O

Article history:
Received 19 November 2019
Received in revised form 8 July 2020
Accepted 3 August 2020
Available online 11 August 2020

Keywords:
C-V2X, cellular-V2I
Safety services
Dynamic ICIC, CS-CoMP
Resource allocation
Co-channel interference

A B S T R A C T

Cellular-based vehicle-to-everything (C-V2X) is one of the emerging and promising techniques to support vehicular communications by enabling both safety-critical and non-safety services. C-V2X communications is a core solution to manage and advance future traffic safety and mobility. In this paper, we design a cellular-based vehicle-to-infrastructure (V2I) communications model for a Manhattan dense urban environment that has many roads deployed in the cell edge region, which results in severe co-channel interference (CCI). Thus, we aim to utilize two cooperative interference management schemes such as dynamic inter-cell interference coordination (ICIC) and coordinated multipoint (CoMP) to mitigate interference and to improve communication reliability. We evaluate the performance of the interference management schemes based on various performance indexes, such as vehicle UE average throughput, vehicle UE received interference, and vehicle UE outage probability. By effectively implementing the dynamic ICIC scheme, we achieve an immense reduction in CCI, which results in the improvement of user (UE) received signal quality. Moreover, we employ coordinated scheduling (CS) CoMP scheme to further mitigate the interference among cells. Finally, by implementing both dynamic ICIC and CS CoMP schemes simultaneously, a meaningful level of performance enhancement is achieved.

1. Introduction

Vehicle-to-everything (V2X) provides communication between vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P), which has been an efficient mean of transportation efficiency enhancement by providing real-time, highly reliable and applicable information flows to ensure safety, mobility and infotainment services. C-V2X terminology introduced by the 3rd Generation Partnership Project (3GPP) in Release 14 [1,2], to support V2X services, utilizing two communication modes of operation, a direct vehicle-to-vehicle communication mode and a network communication mode providing vehicle-to-network communication via operating cellular mobile network. The former pronounced as 'PC5-interface' in 3GPP specification while the latter as 'Uu-Interface' in 3GPP aspects. C-V2X communication composes two transmission mode, V2V and V2I communication using 5.9 GHz spectrum, and V2N communication utilizing already deployed mammoth cellular infrastructure. In this context, C-V2X advancements is to meet the challenges of automated driving to satisfy the travel safety services and to enhance the transportation efficiency.

Recently, attention has been focused on cellular technology that is quickly evolving to meet the requirements of vehicle-to-everything (V2X) communications, and that enables a set of safety-critical and non-safety services associated with an intelligent transportation systems (ITS) [3]. As identified in 3GPP release 14, direct vehicle-to-vehicle (V2V) communications with a PC5 interface reduces latency and supports operations in areas without network coverage and at relative high speeds, while cellular network–assisted vehicle-to-infrastructure (V2I) communications with a Uu-interface can provide high reliability and a data rate to meet non-delay sensitive services. In addition, the ability to leverage the existing cellular infrastructure, with its broad coverage, would accelerate the realization of the safety and efficiency benefits of V2X communications requirements [4–6].

Typically, direct V2V communications is employed with dedicated 5.9 GHz spectrum by considering short-distance communications attribution. However, in a dense urban scenario with a high user density, direct V2V communications with 5.9 GHz spectrum may not fully satisfy the demand of massive data transmission and high reliability requirements. On the contrary, cellular-based networks grant potential to utilize large cell coverage area, already deployed infrastructure and its huge capacity that make it

☆ This work was supported by Inha University Research Grant.
* Corresponding author.
E-mail address: khchang@inha.ac.kr (K. Chang).
URLs: http://www.inha.ac.kr, http://sites.google.com/view/mtrl-lab (K. Chang).

https://doi.org/10.1016/j.vehcom.2020.100282
2214-2096/

reliable solution for vehicle-to-vehicle communications [7]. Hence, cellular V2I communications was introduced to assist in non-delay sensitive safety and entertainment services [8–10]. For the cellular V2I network in a dense urban environment, the major issue is co-channel interference (CCI) [11–13]. In order to mitigate this interference and improve the reliability of the overall system, coordinated interference management such as dynamic inter-cell interference coordination (ICIC) and coordinated scheduling coordinated multipoint (CS CoMP) schemes can be employed.

ICIC is recognized as one of the effective methods to improve the cell edge user's performance in a homogeneous network by allocating orthogonal bandwidth for different cell edge users, which efficiently reduces the chance to cause CCI. Meanwhile, dynamic fractional frequency reuse (FFR) is generally utilized by dynamically allocating the bonus bandwidth (BBW) to a partial reuse (PR) region based on the network load situation of the cell edge region. It should be noted that if there are many users located in the cell edge region, dynamic FFR is more suitable than a static ICIC scheme. The static ICIC technique does not meet the requirements of the rapidly changing operating environment. Moreover, the distribution of resources and power levels to each cell is static i.e. fixed; therefore, it only works efficiently when the load of the network is not changing i.e. constant. Furthermore, it does not involve any kind of cooperation and interaction among the evolved Nodes B (eNBs), hence, it is not feasible for the utmost distribution of frequency. Static ICIC scheme does not manage the dynamic demand of the cell because it controls the cell load only by tuning the power assigned over the different sub-carriers [14–17].

In addition to dynamic ICIC, another cooperative communications scheme, CS CoMP, is also usually used to improve channel conditions for cell edge users. In a CoMP site set, the transmission points can jointly make scheduling decisions and mute severely interfering cells based on a signal-to-interference ratio (SIR) threshold, and thus, improve the UE signal-to-interference-plus-noise ratio (SINR), which is especially effective for cell edge users [18]. There are two main types of CoMP scheme: joint processing (JP) and coordinated scheduling (CS). Although JP might have more throughput gain than CS, it has high implementation complexity due to the requirement for data availability in every participating eNB of the CoMP cooperating set, which makes the scheme unsuitable for CoMP with a non-ideal backhaul. Thus, in this paper, we consider CS CoMP as the cooperating scheme. It should be noted that CoMP may also be utilized to enhance fifth-generation (5G) for new use cases where extreme reliability and system performance are critical, such as the industrial Internet of Things (IoT). In addition, CoMP is also considered as having the ability to enable efficient 5G new radio spectrum sharing (NR-SS) between multiple-operators as well as ultra-reliable low-latency communications.

The major contributions of this study can be summarized as follows.

1. First, this work addresses LTE-V2I modeling in a dense urban scenario. So far, research has been focused on LTE-V2V [19,20] standards, and its system modeling to support the vehicle transmission [21–23]. We design a cellular V2I system model in a dense urban environment according to 3GPP Rel. 14 specifications. There is a fixed distance between the eNBs' positions; besides that, road configuration and vehicle deployment are also considered with the standard norms.

   We focus on the cell edge region as the number of vehicle UEs (VUEs) are randomly deployed at the cell edge. There are many roads situated at the cell edge, which leads to enormous inter-cell interference. This requires a proactive way to serve the vehicles at the cell edge, requiring a high number of physical resource blocks (PRBs) due to a lower SINR than vehicles at the cell center with a high SINR. As the network becomes dense, serving the increased number of cell-edge vehicles becomes more challenging. In order to cope this predicament, we propose implementing two cooperative resource-allocation schemes simultaneously that efficiently manage the resources to users, which satisfies the demand of a vehicles at the cell-edge, whilst reducing the interference at the same time.
2. To deal with the co-channel interference, we introduce the notion of the bonus bandwidth (BBW) in a dynamic FFR that divides the FR spectrum into two parts: (i) fixed FR bandwidth (ii) BBW. Based on the network load, extra available bandwidth efficiently allocates to the edge user that requires additional resources (as explained in detail in section 5) to meet the requirements of the vehicle as well as guaranteeing the communication reliability. Our main concern is to point out the effectiveness of the interference management schemes by considering a practical environment of V2I communications and scheduling procedures.
3. Performance analysis compared with average throughput, outage probability, and the vehicles' received interference. Simulation result shows that the proposed scheme significantly improves the channel quality and overall system reliability.

The rest of the paper is organized as follows. Section 2 presents the system model. In Section 3, the interference scenarios are categorized in order to analyze the CCI, and the cooperative interference management schemes are introduced in Section 4. In Section 5, the performance of the interference management schemes is evaluated using system-level simulation (SLS). Finally, Section 6 concludes the paper.

2. Related work

With regards to autonomous vehicle, research has been largely focused on the integration of V2X information to vehicle density [24], relative speed between vehicles [25] and average vehicle speed [26]. One of the significant areas of interest in today's vehicular industry is the development of technological solutions aimed at improving road safety. Several solutions have been suggested and contributed to provide safety, such as assisted parking systems [27], anti-collision system [28], intelligent navigation systems [29], and driver notification systems [30]. However, potential enhancements can be achieved in providing basic safety and mobility by utilizing cellular-based V2X communication. Therefore, a great attention has been given to the viability of utilizing the cellular technology for making the inter-vehicle data transmission possible [31–33]. However, for a cellular-assisted vehicular network, the major problem causing the data transmission is CCI. In order to deal with CCI, different scheduling and clustering schemes have been proposed in the literature.

In this respect, authors in [34] use multiple network scheduling schemes and optimize them cooperatively in order to mitigate the interference. The proposed scheme consists of semi-persistent scheduling (SPS) in which the initial transmission of the message is scheduled persistently while the retransmission occurs dynamically. Authors imply clustering scheme as well as prediction model, in which eNB is used as an optimization parameter by clustering the vehicle into its coverage area and to estimate the position of the vehicle, respectively. The main difference to this work is optimization criteria and clustering module where vehicles are classified in different clusters having similarity in metric to reduce the interference, which is a different approach from our design, and the authors investigated only the feasibility of their approach. In [35], authors propose the clustering framework in order to serve the vehicle having a lower SINR with the nearby vehicle having a higher SINR. This scheme introduces the offloading mechanism

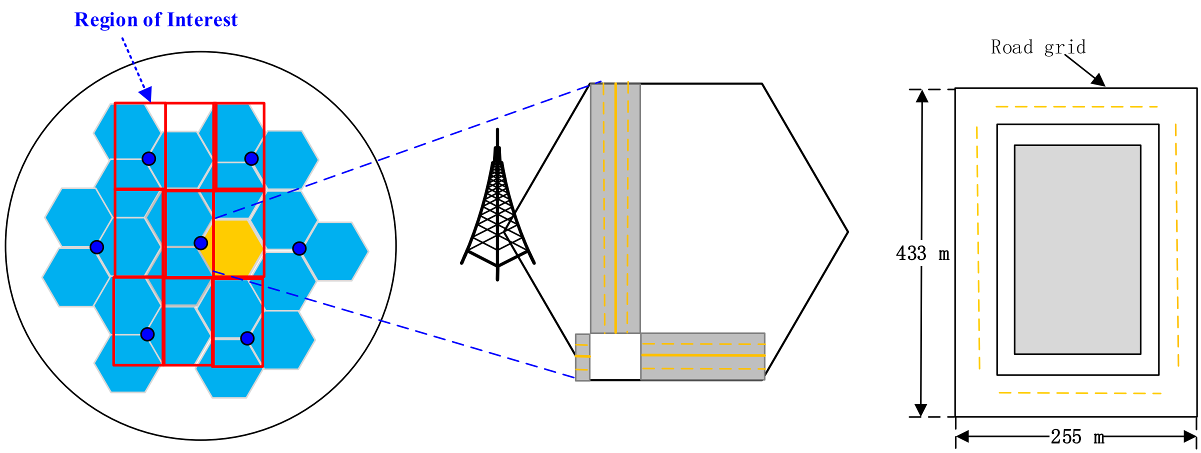


Fig. 1. Cellular V2I network deployment and road configuration.

in which vehicle having a stronger link to the infrastructure provides services through V2V communications to the vehicle having a weaker V2I link. This mechanism is adopted in order to fulfill the requirements of the vehicle to improve its SINR. The major difference to this work is the offloading of the V2I to V2V link by considering the clustering-based approach, which is different from our scheme. The authors did not consider the interference effect caused by the V2I communications, whereas we provide methodology to counter the interference in order to improve the overall throughput of the system by improving the quality of a V2I link. In [36], authors propose the resource management scheme based on the clustering framework. The proposed approach is designed to distinguish the demands of resources from the different types of vehicular links, for instance, V2I and V2V links. The effort is made to enhance the performance of the system in term of latency, sum rate, and throughput. The authors introduce the mechanism of sum-rate optimization to achieve the band sharing and controlling the transmission power that depends on the large-scale fading. The main difference concerning this work is the sum-rate optimization and clustering approaches, which is a very different methodology from our proposed framework. In [36], the authors only inspect the feasibility of their proposed work irrespective of considering the challenges of V2I communications.

3. System model of the cellular V2I network

3GPP defines LTE-V2X in Release 14 to provide the feasible vehicular communication encompassing vehicle-to-vehicle communication (V2V), vehicle-to-infrastructure communication (V2I) and, vehicle-to-pedestrian communication (V2P). The prominent advantage of using LTE technology is considering its already deployed huge infrastructure. To provide the safety and non-safety services, 3GPP standard provides two radio interfaces, namely, LTE-Uu interface that assist V2I communications i.e. enhanced Multimedia Broadcast Multicast Service (eMBMS) and LTE-PC5 interface that supports V2V communication (LTE direct Sidelink at the physical layer).

To fulfill the demands of the automotive industries in terms of automated driving and road traffic safety services, the aforementioned communication protocols are not only substantial but also the coordination schemes play an important role to provide the reliability of the system to stabilize the vehicle-to-infrastructure (V2I) communications and vehicle-to-vehicle (V2V) communications. The coordination scheme possess an intrinsic hybrid characteristic, therefore, it senses the communication between vehicles and infrastructure. In this regards, it collects the information from the long-range cell-edge vehicles and facilitate them to maintain the connection and to meet the demand of the safety services. The eNB performs a double function, where it act as a radio resource scheduler and in the meantime it coordinates the obtained information with the other eNBs drawing out the electronic horizon [37].

3.1. Cellular V2I network deployment and road configuration

The inter-site distance (ISD) of the cellular V2I network is 500 m, and a Manhattan grid layout in a dense urban environment is modeled. There are two lanes in each direction, and four lanes (including opposite directions) for each road. Each road's grid size by distance is 433 m × 255 m. We simulate a 1-tier network to cover the minimum simulation area size (i.e., 1299 m × 750 m) identified by Rel. 14 [38]. As shown in Fig. 1, some road segments are outside the network coverage, which are compensated for by other segments in the network. We adopt the Wrape around mobility model for the urban case according to 3GPP TR 36.885, Release 14 [39]. To simplify the mobility model, we assume all vehicles go straight with a probability of 1. We adopt this postulate to counter the possibility of collision between vehicles, which may displace the actual essence of the designing to figure out the effectiveness of the interference management scheme to counter co-channel interference (CCI).

3.2. Channel model

The general equation to calculate the propagation loss of each transmission link is given as:

$$G = Antenna_{Gain} - PathLoss - Shadowing - Fading \tag{1}$$

Path loss model provided by the 3GPP specification between vehicle and eNB is calculated as:

$$L = 128.1 + 37.6 log10(d) \tag{2}$$

where d is the distance between transmitter (Tx) and receiver (Rx) in kilometers, and L is the loss that occurs due to distance between vehicle and eNB [38].

Shadowing is given by using a log-normal distribution with a standard deviation of 8 dB. The decorrelation distance is 50 m. The shadowing correlation factor is 0.5 for the shadowing between eNB sites, and 1.0 is used for shadowing between sectors in the same eNB site. The penetration loss is 0 dB [38].

Fast fading is variation or attenuation of a signal with various variables. In this paper, fast fading is generated according to a spatial channel model (SCM) non–line of sight (NLOS) scenario with fixed large-scale parameters [38].

A 3D antenna pattern is generally utilized for eNBs, which can be represented as follows:

$$A(\theta,\phi) = -min[A_v(\theta_v) + A_H(\phi_H), A_m] \quad (3)$$

where A_v and A_H are the vertical and horizontal cut, respectively. θ_v and ϕ_H are the antenna direction angles on the vertical and horizontal plane, respectively. A_m is the backward attenuation while $A(\theta,\phi)$ is the total attenuation.

3.3. UE distribution via one-dimensional Poisson point process

The vehicle UEs are dropped on the roads according to a spatial Poisson process that defines a point process, whereby point events occur within a given area of interest [40]. Due to the assumption of vehicle's speed, each lane has same vehicle density, and vehicle location updates every 100 ms. A 1-D Poisson point process (PPP) is an appropriate method for modeling the locations of vehicles in each lane. The number of vehicles in each lane follows a Poisson distribution, and a uniform distribution is typically applied to determine each vehicle's position.

Mathematically, the description of a Poisson point distribution which provides the probability of number of points $N(A)$ equals to k in each lane is given by:

$$P(N(A)=k) = \frac{e^{-\lambda|A|}(\lambda|A|)^k}{k!} \quad for \quad k=0,1,2,3,...,N \quad (4)$$

where $N(A)$ is the number of points in each lane, the parameter λ is the density of the points in each lane, and $|A|$ denotes the length of the lane.

After deciding density λ, we can uniformly scatter the number of points obtained by the PPP over each lane. We apply the following inequality to generate a Poisson $\lambda|A|$ number of points:

$$\prod_{i=1}^{N+1} U_i < e^{-\lambda} \quad (5)$$

where U_1,U_2,..., are independently uniform (0,1), and N is the number of vehicles in each lane as obtained from the inequality.

3.4. Proportional scheduler

It should be noted that a proportional fair scheduler is generally used to achieve good performance. The scheduler utilizes channel quality indicator (CQI) information estimated from received signals. Based on the CQI transmitted by the vehicle, resource allocation is performed [41]. CQI estimation from the received signal and for each vehicle is used to calculate the SINR for every PRB. In order to model a realistic Long Term Evolution Advanced (LTE-A) system, periodic and delayed CQI is assumed. For each vehicle, a modulation and coding rate scheme (MCS) is selected based on the SINR. The Proportional fairness f for each vehicle m can be achieved [42] as follows:

$$f = argmax \frac{R_m}{R^{\top}_{m,Avg}} \quad (6)$$

where R_m is the instantaneous rate for vehicle m, and $R^{\top}_{m,Avg}$ is the average rate for user m.

3.5. Abstraction of the physical layer

Abstraction of the physical layer (PHY) is to get the block error rate (BLER) for each transport block by using a specific modulation and coding level to calculate UE throughput. In an LTE-A system, there are 15 CQI indexes corresponding to different modulation and coding rate schemes (MCS), and various MCS levels can achieve different spectral efficiencies. To get the BLER in an SLS and to reduce signal processing complexity, we utilize link-level simulation (LLS) curves from an additive white Gaussian noise (AWGN) channel. In a low-speed dense urban scenario, perfect time and frequency synchronization are assumed for the receiver. The signal-to-interference-plus-noise ratio is calculated for each PRB of each vehicle. In this paper, mutual information-based exponential SINR mapping (MIESM) is utilized for link-to-system mapping [43].

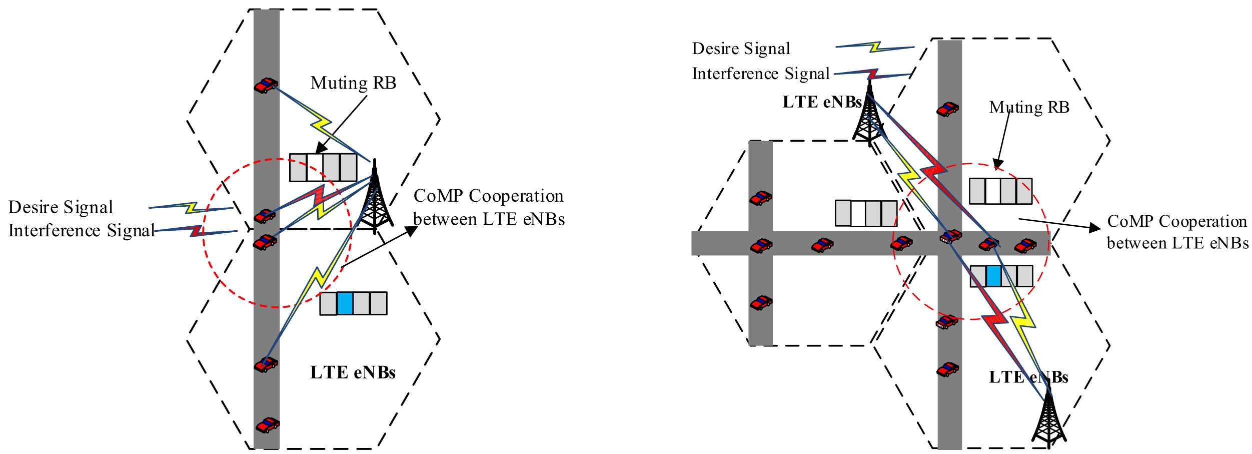
4. Analysis of co-channel interference in the cellular V2I network

Cellular communication systems mainly experience two kinds of interference, namely, intra-cell interference and inter-cell interference. In the former, interference occurs within the same cell between the adjacent frequency channels due to adjacency in their frequencies or maybe due to power leakage from the one channel to its next channel. In the latter, however, interference produces between the two cells due to same frequency utilization which interfere with each others, hence, termed as co-channel interference (CCI).

In LTE network, the frequency spectrum divides into many channels, each consisting of a number of continuous orthogonal OFDM subcarriers [44]. Due to orthogonality of the subcarrier, the intra-cell interference reduces remarkably. The time domain is partitioned into different time slots containing a successive OFDM symbols. The OFDM symbols in each slot determines on the type of cyclic prefix used to encounter the co-channel interference. The smallest unit that can be utilized to schedule resource is termed as PRB. Each frame consists of number of continuous time slots, in the same fashion; a super-frame builds with multiple frames in a row. On demand of the user, number of PRBs is allocated to the single users at a time within a cell. The one PRB assigns to one user at a single time, however, the same PRB can also be allocated to the different users in neighboring cell. This reuse at the same time causes collision of RBs which leads to CCI [45]. This collision degrades the overall performance of the system by effecting the Signal to Interference and Noise Ratio (SINR) that correlates with the resource block collision.

ICIC aims to control the CCI by decreasing the collision probability of RBs as well as improve the system performance in terms of data rate and spectral efficiency especially at the cell edge. ICIC scheme uses the frequency-reuse designing strategies to restrict or distribute the resources in both time and frequency domains while maintaining the power constraint among the users in different cells. These strategies are meant to enhance the SINR and build a system to support maximum users. The transmission power of the eNB must be taken carefully that it does not exceed the maximum bearable power and cause no harm to the user SINR. The basic idea behind the ICIC is to categorize the users based on their average SINR into users' divisions known as cell regions. The different frequency-reuse factor applies to the different cell regions [46].

ICIC scheme has been studied under different network environments and traffic load conditions mainly classified into static and dynamic scenario techniques, similarly, centralized and distributed scenario techniques, to reduce the effect of co-channel interference. Therefore, in this regards, efforts have been conducted to utilize ICIC considering the static and dynamic allocation of resources, such as Partial-Frequency Reuse [47], Hard-Frequency Reuse as Reuse-3 [48], and Soft-Frequency Reuse [49]. Furthermore, many attempts have also been made on the distribution of resources in a coordinated framework, like, frequency collaboration between the eNBs [50], and spectrum access in an intelligent be-



(a) When the neighbouring vehicle from the different cell schedule with the same PRBs causing Co-Channel Interference.

(b) Vehicle acquires CoMP assistance to counter the Co-Channel Interference.

Fig. 2. C-V2I communication network with CS CoMP.

havior [51]. All these efforts are made to reduce the co-channel interference to enhance the overall system performance particularly cell-edge users' throughput.

It can be clearly seen from the Fig. 2a that the vehicle UEs are situated at the edge of the cell because they are distributed randomly in the intra-cell region. According to the network and road deployment, we observe that some intersections and roads are located at the cell-edge region. As we know, edge regions are critical geo-locations that need more attention to maintain reliability and to improve traffic efficiency. When neighboring vehicles belonging to a different cell are scheduled with the same PRBs, it will cause severe CCI as shown in Fig. 2b. It is depicting the co-channel interference scenarios for both inter-sector and inter-site cases. In order to mitigate this type of interference, a different spectral bandwidth is allocated to different cell edge regions by implementing a dynamic FFR scheme. To further improve performance, CS CoMP is utilized. The eNBs exchange the PRBs' requests for information to each other, and cooperatively make the muting decision for each PRB.

5. Proposed coordinated resource allocation schemes

Radio resource management plays an important role to satisfy the quality-of-services (QoS) demand of vehicular communication [52]. To fulfill the quality of service (QoS) demands of vehicular communication in heterogeneous traffic network, performance of joint resource allocation and power control for V2V and V2I communication has been investigated in [53] where Qos constraint for V2V assure high reliability, low latency while guaranteeing the maximum sum rate for V2I communication. In the same context, network slicing mechanism adopts in allocating the radio resource for V2X network [54] while considering the system performance in terms of latency, manageable rate and outage. In all these schemes, they have not considered the cell edge users requirements while allocating the radio resources. In order to achieve the desirable vision of vehicular communication regarding safety services, we propose the cooperative resource allocation schemes to satisfy the demands of the cell-edge user.

5.1. Dynamic ICIC for cooperative communications in a cellular V2I network

The main idea of FFR is to utilize frequency reuse factors for cell edge and cell center users, which is a promising technique to improve cell edge user performance in a cellular network [55]. In this paper, we model the cellular V2I network layout according to 3GPP Rel. 14, and observe that there are some roads and intersections deployed in the cell edge region. Therefore, we employ a dynamic FFR scheme in this work, where one cell is divided into two sub-areas to mitigate cell edge co-channel interference.

The basic principle of FFR is to divide cells into cell edge and cell center zones. Correspondingly, the total bandwidth is partitioned into full reuse (FR) spectrum with reuse-1 and partial reuse (PR) spectrum with reuse-3 for cell center and cell edge regions, respectively [56]. However, static FFR cannot take network load into account due to the fixed bandwidth division. Considering the network load situation, an effective dynamic FFR scheme is usually utilized in many scenarios. In dynamic FFR, the notion of bonus bandwidth (BBW) is applied. We further divide the FR spectrum into two parts which include fixed FR bandwidth and BBW so that extra available BW should be efficiently allocated to the edge users that requires more resources [57]. Fig. 3a depicts the dynamic FFR scheme applied in three different cells, which efficiently guarantees communications reliability for the intersection and cell edge vehicles. The spectrum division is dynamic based on the network load situation. For dynamic FFR, the total bandwidth is divided into seven portions, which are given as follows:

$$\begin{aligned} BW_{Total} = [BW_{FR} + (BW_{B1} + BW_{B2} \\ + BW_{B3})_{Bonusband}]_{FRband} \\ +[BW_{PR1} + BW_{PR2} + BW_{PR3}]_{PRband} \end{aligned} \tag{7}$$

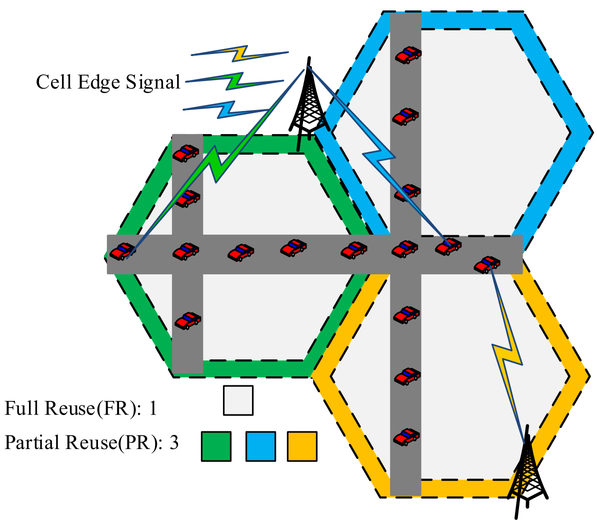
Initially, the BBW is allocated to an FR zone. When FR zone vehicle UEs need more resources, BBW will be assigned to FR zone vehicle UEs as shown in Fig. 3b. The PR zone is equally divided into three portions, shown as follows:

$$BW_{PR1} = BW_{PR2} = BW_{PR1} = \frac{1}{3}(BW_{Total} - BW_{FR}) \tag{8}$$

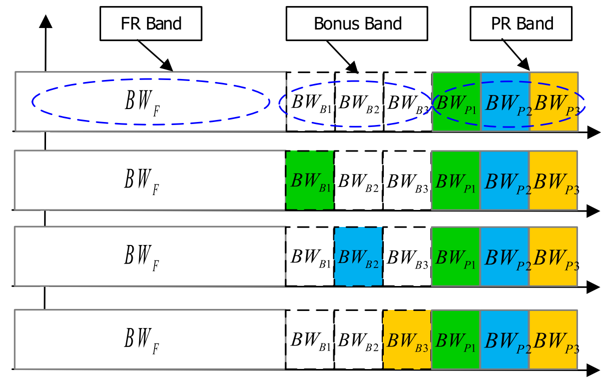
To distinguish the FR and PR zone users, an SINR threshold is usually utilized, as follows:

$$\begin{aligned} SINR_m < SINR_{threshold} \; for \; PR \; zone \; users \\ SINR_m > SINR_{threshold} \; for \; FR \; zone \; users \end{aligned} \tag{9}$$

The flowchart in Fig. 4 shows the implementation steps of the dynamic FFR scheme. In the beginning, bonus band is allocated



(a) Dynamic FFR scheme is applied in three cells. The white portion in the centre showing the FR Band while the colored portions at the corner showing the cell-edge region. The BBW is allocated to the cell-edge user when the vehicle at the edge demands.



(b) Total Bandwidth is divided into seven shares. Maximum bandwidth is reserved for the Full-Reuse Spectrum while the remaining portions has been divided equally into BBW and Partial-Reuse spectrum. Further, the BBW is separated into three slice which are only cached for the edge-users requiring more resources due to lower SINR in order to maintain the reliability of the system.

Fig. 3. Bandwidth partitioning with dynamic FFR.

to the FR zone. During the band assignment, vehicle UE sends a request to its corresponding eNB, in which it specifies its position and location in the environment. Utilizing the information received by the vehicle UE, the eNB comes to know about the traffic load in the PR zone. If the traffic increases in the PR zone, to maintain the quality of service, the eNB finds the available set of BBW and allocates it to the demanding vehicle UE in the PR zone, and switches all the services, which are using the BBW bands, to other possible bands to allocate them to demanding vehicle UEs in PR zone.

5.2. CS CoMP between cellular eNBs

The CoMP framework was first introduced by 3GPP in Release 12, coming up with more sophisticated coordination methods to tackle the co-channel interference (CCI) in order to enhance the performance of cell-edge users. Generally, the cell-edge user is able to transmit and receive signals to or from different sites. The CoMP principle [58] allows coordination among signals transmitted from different cell sites to reinforce the received signal quality particularly the spectral efficiency of edge-users by encountering CCI.

There are two approaches in CoMP architecture, namely Centralized coordination and Distributed coordination. The number of cell sites involved in coordination to overcome the CCI is said to be CoMP set. CoMP is mainly classified into two schemes, Coordinated Scheduling (CS) and Joint Processing (JS). In the former schemes, the shared information stays only within the serving cell sites and the decision is made dynamically after the coordination in the CoMP set. It makes CS-CoMP more reliable, easy to implement, and provides robust and fast coordination to manage the CCI. In the latter, coordinating cell sites jointly process and optimize the edge user as a unique entity to enhance the performance of the edge user. Hence, it has high implementation complexity and it requires data availability in each participating eNB in CoMP set which makes incompatible for CoMP with a non-ideal backhaul [59].

5.2.1. Proposed dynamic coordinated muting-based scheduling process

In this section, a dynamic cooperative muting–based CS CoMP scheme is employed among eNBs to reduce undesirable interference, and one central scheduler is used to make the muting decisions and assign the PRBs. Each eNB identifies the vehicle UE that needs CoMP assistance based on UE feedback as show in Fig. 2b. CoMP assistance is performed via coordinated link. Unlike the cell-specific muting [60–62] applied in some research, in this paper, we consider PRB-specific muting, and implement inter-site as well as inter-sector CS CoMP for all the eNBs. Therefore, the CoMP set includes the whole of the transmission points in the 1-tier network. It can be represented as follows:

$$C_{CoMP} = [Site_1, Site_2, ..., Site_7] \tag{10}$$

where all seven sites are included in the CoMP set. To decide which eNBs are used for CoMP assistance, an SIR threshold is usually applied.

By enabling cooperation between the eNBs, higher spectrum efficiency can be achieved, compared to making the scheduling independently for each cell. To determine if UE needs CoMP assistance from neighboring cells, accurate channel state information (CSI) is essential to achieving good performance from vehicular communications [63]. The CSI carries the information about when vehicle UE gets interference from neighboring cells, and when there is no interference from neighboring cells. The central scheduler cooperatively processes the information collected from each eNB. In this regard, the CoMP users report the CSI to the central scheduler for all participating eNBs in the CoMP set to make proper scheduling decisions [64]. The working operation of CS CoMP is shown in Fig. 5. When vehicle UE requests for the CoMP assistance due to interfering signal from the neighboring eNB having the same PRBs. Therefore, the aggressor neighbor eNB mutes the same PRB to minimize the interference. To decide which vehicle UE requires CoMP assistance and which neighboring cells should give

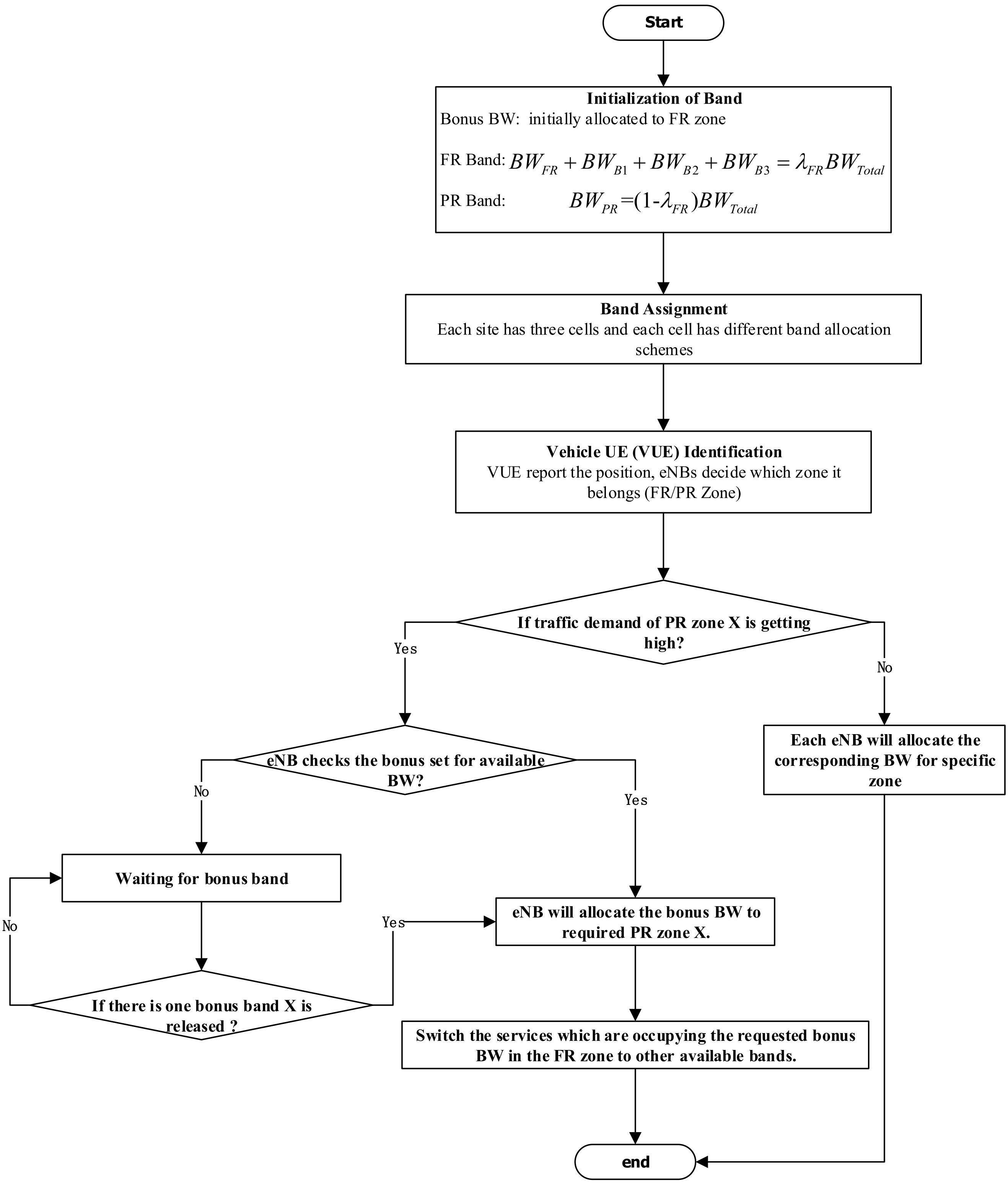


Fig. 4. Flow chart of dynamic FFR procedures.

that assistance, the proper conditions should be evaluated with the following equation:

$$SIR_m^n > SIR_{Threshold} \tag{11}$$

where SIR_m^n is the signal-to-interference ratio for vehicle UE m, and n is the index of interfering cells. By checking the vehicle UE SIR value, we can find out if the vehicle UE needs CoMP assistance, and the eNB will make the decision to inform neighboring eNBs for muting or utilizing the same RB.

5.2.2. SINR and throughput calculation

SINR for CoMP [41] vehicle UEs is calculated as:

$$SINR_{m,u,CoMP}^n = \frac{G_{m,u}^n P_{m,u}^n}{\sum_{k \neq n, k \in C_{CoMP} - C_m - 1} G_{m,u}^k P_{m,u}^k + \eta_m} \tag{12}$$

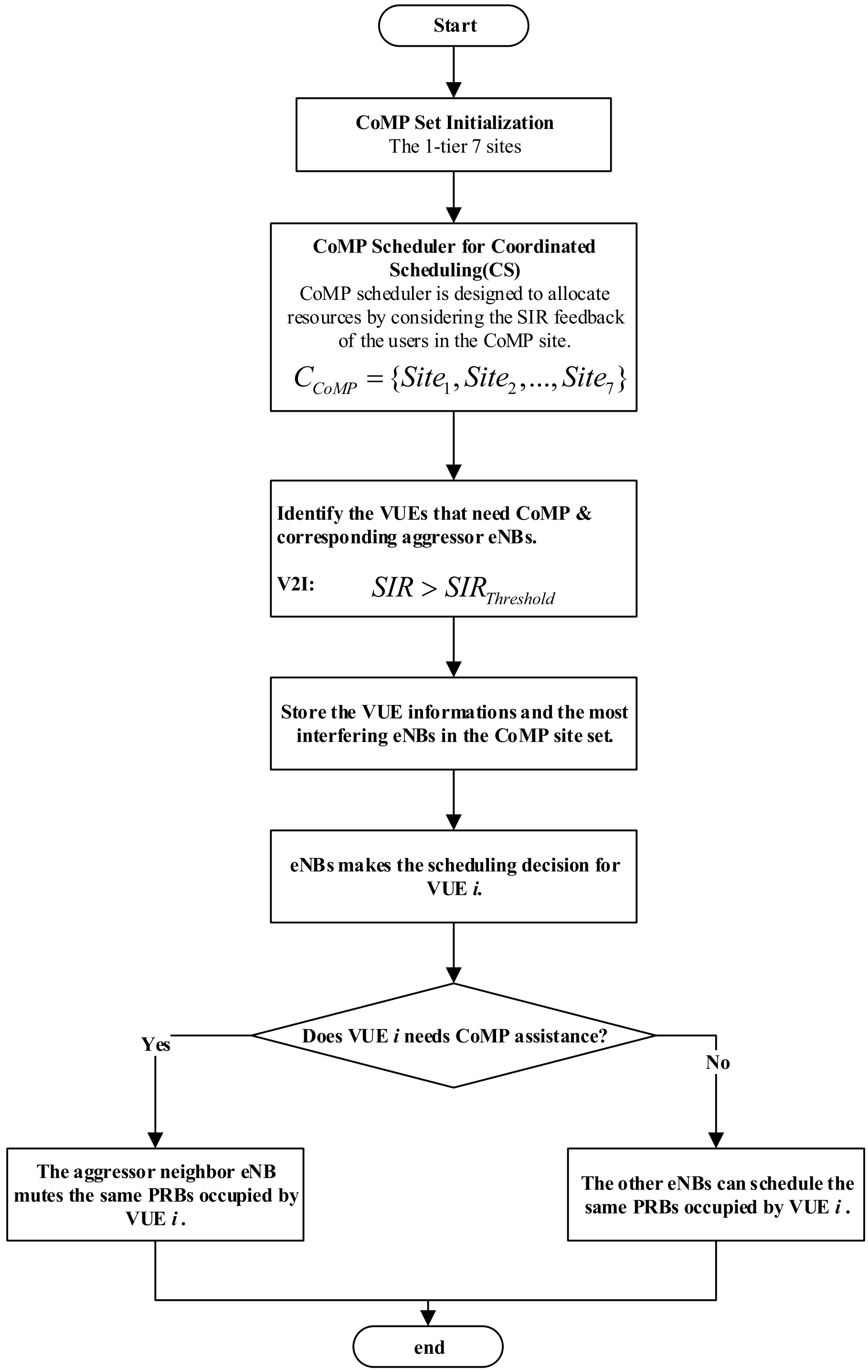


Fig. 5. Flow chart of the CS CoMP procedures.

Similarly, the SINR for non-CoMP [41] vehicle UEs is calculated as:

$$SINR^n_{m,u,non\_CoMP} = \frac{G^n_{m,u} P^n_{m,u}}{\sum_{k\neq n,k\in 1}^{C_{CoMP}} G^k_{m,u} P^k_{m,u} + \eta_m} \tag{13}$$

where $G^n_{m,u} P^n_{m,u}$ is the power received by vehicle UE m on PRB u in cell n after considering channel gain, and $G^k_{m,u} P^k_{m,u}$ denotes the co-channel interference from the neighboring cell k on the same PRB u.

Similarly, the data rate for CoMP vehicle UEs can be calculated as:

$$\begin{aligned} r^n_{m,u,CoMP} &= B_{CoMP}\, log_2\,(1 + SINR^n_{m,u,CoMP}) \\ &= B_{CoMP}\, log_2\,(1 + \frac{G^n_{m,u} P^n_{m,u}}{\sum_{k\neq n,k\in C_{CoMP}-C_m-1} G^k_{m,u} P^k_{m,u} + \eta_m}) \end{aligned} \tag{14}$$

The data rate for non-CoMP vehicle UEs can be calculated as:

$$\begin{aligned} r^n_{m,u,non\_CoMP} &= B_{non\_CoMP}\, log_2\,(1 + SINR^n_{m,u,non\_CoMP}) \\ &= B_{non\_CoMP}\, log_2\,(1 + \frac{G^n_{m,u} P^n_{m,u}}{\sum_{k\neq n,k\in 1}^{C_{CoMP}} G^k_{m,u} P^k_{m,u} + \eta_m}) \end{aligned} \tag{15}$$

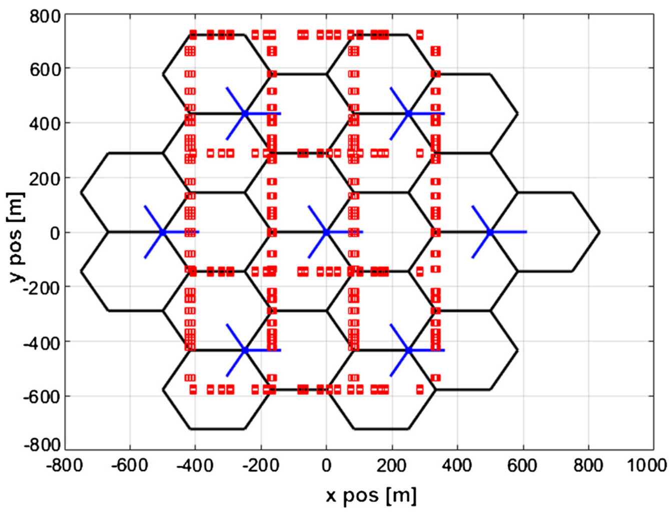


Fig. 6. Vehicle distribution in the cellular V2I network: It indicates the 1-tier LTE-Network deployment. The blue star-shaped exhibits the eNBs stationing and the red lines depict the road distribution over the 1-tier LTE Network.

where B_{CoMP} and B_{non_CoMP} denote the bandwidth for CoMP and non-CoMP vehicle UEs, respectively, and $r^{n}_{m,u,CoMP}$ and r^{n}_{m,u,non_CoMP} are the data rates that can be calculated.

Hence, the overall system data rate for CoMP and non-CoMP vehicle UEs is expressed as follows:

$$R_{CoMP+non\_CoMP} = \sum_{n\in N} \sum_{m\in U_n, u\in RB^n_m} r^{n}_{m,u,CoMP} + \sum_{n\in N} \sum_{m\in U_n, u\in RB^n_m} r^{n}_{m,u,non\_CoMP} \quad (16)$$

where U_n is a set of vehicle UEs in cell n. N denotes the set of cells. $R_{CoMP+non\_CoMP}$ is the total system throughput in bits per second. RB^n_m is the set of RBs for user m scheduled by cell n.

6. Performance evaluation of cooperative resource allocation schemes

To evaluate the performance of the cooperative resource allocation schemes, we developed MATLAB based system-level simulation of a 1-tier LTE-V2I network. The main SLS parameters are summarized in Table 1. We chose the cooperative awareness message (CAM) traffic model for V2I communications.

Fig. 6 shows the vehicle UEs distribution over the 1-tier LTE network. We drop the vehicle UEs on the road using spatial Poisson process as explained in section 3.3. The vehicle position updated every 100 msec. It encompasses road framework consisting of two lane in each direction and total four lanes including opposite direction for each road according to 3GPP specifications as explained in section 3.1. It should be noted that some roads segments are outside the 1-tier network coverage, but are compensated for by other segments of the network.

Fig. 7 exhibits the SINR of the vehicle UE located in different cell edge regions and non–cell edge regions, where the x-axis indicates the y-coordinate of the vehicle UE position. We assume the x-axis is constant, because the vehicle can be deployed uniformly on the road, and also, the vehicle density is high. The red curve indicates the SINR of the vehicle UE without any enhanced techniques. We can possibly observe that the vehicle UE sometime suffers high interference at the cell edge region, due to such interference vehicle received SINR degrades abruptly and drops to -10 dB. This lower SINR deteriorates the overall system performance and, hence, effects the system throughput.

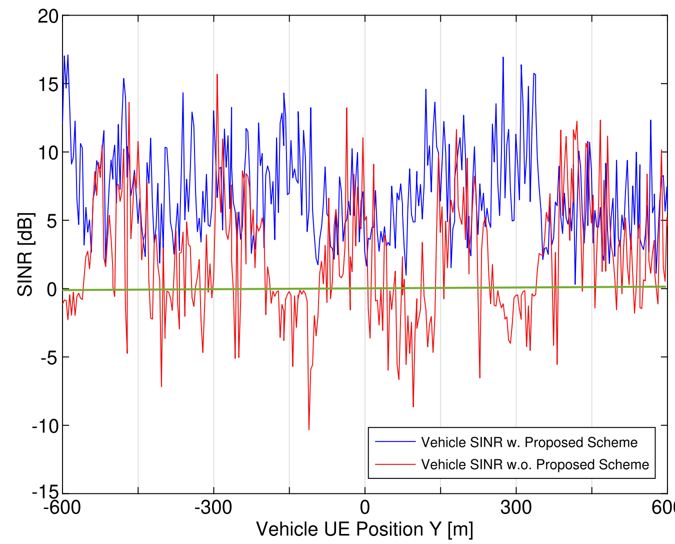


Fig. 7. Vehicle SINR; Red-curve indicates SINR without any Interference management scheme while Blue-curve manifests SINR utilizing enhanced scheme encompasses Dynamic ICIC and CS CoMP. The depiction clearly shows vehicle sometime suffers high interference which degrades the SINR to -10 dB. In this regard, using proposed interference mitigation scheme reduces the effect of the co-channel interference, and hence vehicle experiences SINR higher than 0 dB.

Table 1
Simulation parameters.

Parameter	Value
Cellular Layout	Urban: 21cell Inter-site Distance (ISD): 500 m Manhattan Grid
Carrier Frequency	2 GHz
Bandwidth	10 MHz
RB Bandwidth	180 kHz
Transmission Mode	SIMO Transmission
No. of PRBs	50
Path Loss	Urban Macro 3GPP TR 36.885
Shadowing	Log-normal Distribution Mean: 0 dB St. Dev.: 8 dB Correlation b/w eNBs/sectors: 0.5/1
Fading	Spatial Channel Model (SCM) N-LOS
Noise Spectral Density	-174 dB m/Hz
Mobility	Dense Urban Scenario 60 km/h [39]
Tx power	46 dB m
Maximum Antenna Gain	15 dBi
Minimum Coupling Loss	70 dB
L2S Mapping	MIESM
UE Receiver	Zero Forcing
Traffic Model	CAM
Scheduler	Proportional Fair (PF)

Similarly, the blue curve shows the SINR of vehicle UE located in different cell edge regions and non–cell edge regions rises up using the cooperative interference management schemes. Dynamic ICIC reduces interference by efficiently allocating the bonus bandwidth to the cell-edge vehicle UE. In addition, utilizing CS-CoMP further decreases the effect of co-channel interference. We can un-

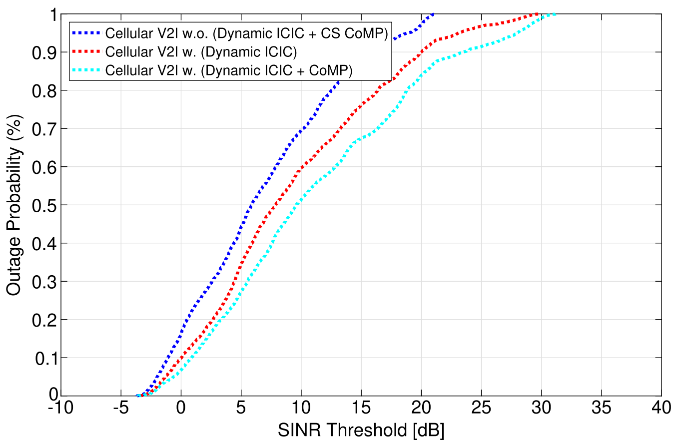


Fig. 8. UE outage probability.

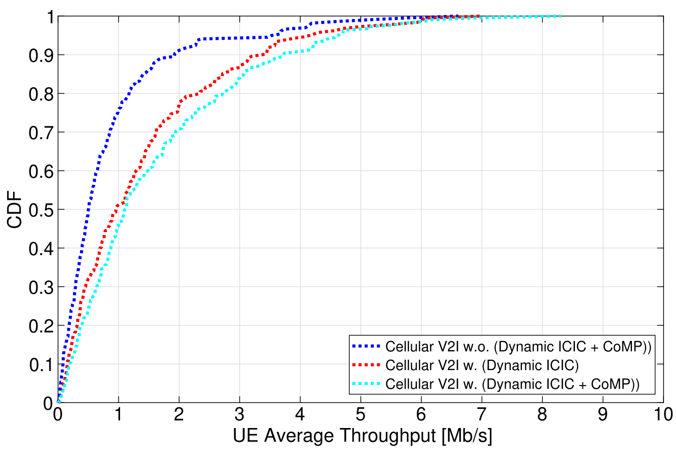


Fig. 9. UE average throughput.

doubtedly regard that the SINR of the cell edge vehicle UE immediately improved, and almost all cell edge vehicle UEs experienced SINR more than 0 dB, which enhances, and ensures the effectiveness of using dynamic ICIC and CS CoMP simultaneously.

As shown in Fig. 8, the channel quality for vehicle UEs greatly improved by using cooperative management schemes, i.e., dynamic ICIC and CS CoMP simultaneously. The outage probability equation is given as follows:

$$P_{outage} = 1 - P_b(SINR \geq SINR\_Threshold) \quad (17)$$

where $P_b(SINR \geq SINR\_Threshold)$ means the probability that the vehicle UE Rx SINR is higher than the SINR threshold, and then, the vehicle UE is not considered to be experiencing an outage.

It can clearly be seen from Fig. 8 that the outage probability decreases by using the proposed cooperative resource allocation schemes. If we compare the outage probability at the 5 dB SINR threshold without any resource allocation schemes, we can easily see that 44% of vehicle UEs experienced an outage. Applying the dynamic ICIC scheme, the SINR of cell edge vehicle UEs increased effectively, so that the percentage of vehicle UEs experiencing an outage decreased to 34%. This is due to the orthogonal bandwidth for cell edge users from different cells. Moreover, performing dynamic ICIC and CS CoMP simultaneously greatly reduced the outage probability, and improved the channel quality, which resulted in only 27% of vehicle UEs experiencing an outage. This indicates that using resource allocation schemes benefits the system.

The enhancement in the throughput can be clearly observed from the Fig. 9. We compare the throughput evaluation performance at 50% of the cumulative distribution function (CDF). The

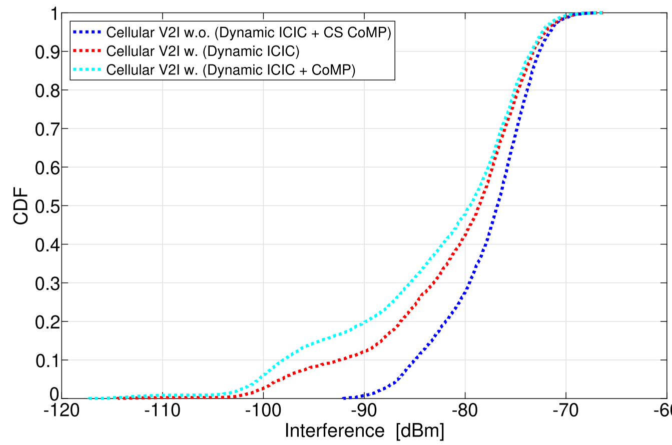


Fig. 10. UE Rx interference.

average throughput can be calculated [65] according to equation (18) as follows:

$$Throughput = \frac{TB}{Accounted\_TTIs * TTI\_Time} Mbps \quad (18)$$

where TB is the total bits for receiver vehicle UE, and where $Accounted\_TTIs$ represents the maximum number of transmission time intervals ($TTIs$) in which RBs assigned to receiver UE. We compared the throughput performance at 50% of CDF. It can clearly be seen that the throughput without any schemes is only 0.5 Mbps, and using dynamic ICIC increases to 0.96 Mbps. Hence, dynamic FFR provides better throughput performance by allocating partial band and bonus band, which gives 46% better performance. In addition, we operate CS-CoMP in cooperation with dynamic ICIC which further augmented throughput of the system. When both dynamic ICIC and CS-CoMP schemes are employed simultaneously in a cooperate framework, the highest throughout is achieved. This enhancement is due to the two promising cooperative interference management schemes: (a) dynamic ICIC significantly reduced the chance of co-channel interference by using a specific separate bandwidth at the cell edge, and (b) the added CS-CoMP mutes the high-interfering eNBs to reduce the co-channel interference. Therefore, utilizing both schemes at once, the average and overall throughput improved.

Fig. 10 shows the aggregate interference performance from all neighboring eNBs except the serving eNB. The interference equation is given by:

$$I_k = \sum_{k \neq n, k=1} G^k_{m,u} P^k_{m,u} + \eta_m \quad (19)$$

where I_k is the aggregate interference received from all neighboring cells k, except for the serving eNB. $G^k_{m,u}$ is the channel gain for user m, $P^k_{m,u}$ is the transmit power from the eNBs to user m on PRB u, and η is the thermal noise per PRB.

It can clearly be seen that the scenario with dynamic ICIC has less interference than the scenario without any interference management schemes, because the interference is greatly decreased by using orthogonal bandwidth for cell edge vehicle UEs. At 50% CDF, vehicle UEs received interference at -76.8 dBm without any interference management scheme. Applying dynamic ICIC, the UEs' received interference decreased to -78.63 dBm. Furthermore, the vehicle UEs experienced much lower interference of -79.53 dBm when both dynamic ICIC and CS CoMP were implemented simultaneously. The above comparison clearly proves the benefits from utilizing cooperative interference management schemes in a dense urban environment for cellular V2I communications.

7. Conclusions

In this paper, we analyze the co-channel interference (CCI) for a cellular V2I network in a dense urban environment. We employ the two interference management schemes simultaneously in a cooperative framework to mitigate the CCI and to enhance the overall system throughput. We introduce the notion of the bonus bandwidth (BBW) into the spectrum utilizing the dynamic ICIC, which allocate to the high-demanding PR zones to increase the user-received signal quality. Furthermore, we added dynamic cooperative CS-CoMP scheme by using the PRB-specific muting decision mechanism to further increase the reliability of the system. Each eNB identifies the vehicle UE that needs CoMP assistant based on the vehicle UE feedback. This results in further mitigation of the CCI as well as reduces the outage probability and improves the SINR of the vehicle UE. In Fig. 7, the SINR of almost all the vehicle UEs is larger than 0 dB due to significant reduction of the interference. It indicates that the channel quality for each vehicle UE is remarkably improved. Simulation results show that throughput of the system increases 63% and outage probability reduces 17%, which ensures the effectiveness of our proposed approach. Our next target is to analyze the machine-learning algorithms for the 5G-V2X communications considering the collision avoidance strategies at the road cross-sections and to introduce the framework, which intelligently manages the resources and fulfils the demands of the vehicles.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by Inha University Research Grant.

References

[1] G. T. 22.885, Study on lte support for vehicle to everything (v2x) services, https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2898, 2015.
[2] G. T. 36.300, Evolved universal terrestrial radio access (e-utra) and evolved universal terrestrial radio access network (e-utran), https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2430 2015.
[3] S. Chen, J. Hu, Y. Shi, Y. Peng, J. Fang, R. Zhao, L. Zhao, Vehicle-to-everything (V2X) services supported by LTE-based systems and 5G, IEEE Commun. Stand. Mag. 1 (2) (2017) 70–76.
[4] G. T. 22.886, Study on enhancement of 3gpp support for 5g v2x services, https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3108, 2017.
[5] A. Bazzi, B.M. Masini, A. Zanella, I. Thibault, On the performance of IEEE 802.11 p and LTE-V2V for the cooperative awareness of connected vehicles, IEEE Trans. Veh. Technol. 66 (11) (2017) 10419–10432.
[6] J. Lianghai, A. Weinand, B. Han, H.D. Schotten, Feasibility study of enabling V2X communications by LTE-uu radio interface, in: 2017 IEEE/CIC International Conference on Communications in China (ICCC), IEEE, 2017, pp. 1–6.
[7] K. Abboud, H.A. Omar, W. Zhuang, Interworking of DSRC and cellular network technologies for V2X communications: a survey, IEEE Trans. Veh. Technol. 65 (12) (2016) 9457–9470.
[8] H. Peng, D. Li, Q. Ye, K. Abboud, H. Zhao, W. Zhuang, X. Shen, Resource allocation for cellular-based inter-vehicle communications in autonomous multiplatoons, IEEE Trans. Veh. Technol. 66 (12) (2017) 11249–11263.
[9] R. Molina-Masegosa, J. Gozalvez, Lte-V for sidelink 5G V2X vehicular communications: a new 5G technology for short-range vehicle-to-everything communications, IEEE Veh. Technol. Mag. 12 (4) (2017) 30–39.
[10] M. Shi, C. Lu, Y. Zhang, D. Yao, DSRC and LTE-V communication performance evaluation and improvement based on typical V2X application at intersection, in: 2017 Chinese Automation Congress (CAC), IEEE, 2017, pp. 556–561.
[11] X. Wen, J. Chen, Z. Hu, Z. Lu, A p-opportunistic channel access scheme for interference mitigation between V2V and V2I communications, IEEE Int. Things J. (2020).
[12] D. Du, X. Jian, X. Wu, Y. Tan, X. Zeng, S. Huang, Y. Li, 3d spatial characteristics of C-V2X communication interference, Electronics 8 (6) (2019) 718.
[13] P.S. Bithas, G.P. Efthymoglou, A.G. Kanatas, Intervehicular communication systems under co-channel interference and outdated channel estimates, in: 2016 IEEE International Conference on Communications (ICC), IEEE, 2016, pp. 1–6.
[14] G. T. 36.814, Further advancements for e-utra physical layer aspects, https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2493, 2010.
[15] R. Agrawal, A. Bedekar, S. Kalyanasundaram, N. Arulselvan, T. Kolding, H. Kroener, Centralized and decentralized coordinated scheduling with muting, in: 2014 IEEE 79th Vehicular Technology Conference, VTC Spring, IEEE, 2014, pp. 1–5.
[16] M. Rahman, H. Yanikomeroglu, Enhancing cell-edge performance: a downlink dynamic interference avoidance scheme with inter-cell coordination, IEEE Trans. Wirel. Commun. 9 (4) (2010) 1414–1425.
[17] G. T. 36.819, Coordinated multi-point operation for lte physical layer aspects, https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2498, 2011.
[18] Y. Li, Z. Kaleem, K. Chang, Interference-aware resource-sharing scheme for multiple D2D group communications underlaying cellular networks, Wirel. Pers. Commun. 90 (2) (2016) 749–768.
[19] C. Han, M. Dianati, R. Tafazolli, R. Kernchen, X. Shen, Analytical study of the IEEE 802.11 p mac sublayer in vehicular networks, IEEE Trans. Intell. Transp. Syst. 13 (2) (2012) 873–886.
[20] A. Bazzi, C. Campolo, B.M. Masini, A. Molinaro, A. Zanella, A.O. Berthet, Enhancing cooperative driving in IEEE 802.11 vehicular networks through full-duplex radios, IEEE Trans. Wirel. Commun. 17 (4) (2018) 2402–2416.
[21] A. Bazzi, G. Cecchini, A. Zanella, B.M. Masini, Study of the impact of phy and mac parameters in 3GPP C-V2V mode 4, IEEE Access 6 (2018) 71685–71698.
[22] S. Park, B. Kim, H. Yoon, S. Choi, RA-eV2V: relaying systems for LTE-V2V communications, J. Commun. Netw. 20 (4) (2018) 396–405.
[23] M. Gonzalez-Martín, M. Sepulcre, R. Molina-Masegosa, J. Gozalvez, Analytical models of the performance of C-V2X mode 4 vehicular communications, IEEE Trans. Veh. Technol. 68 (2) (2018) 1155–1166.
[24] X. Wu, S. Subramanian, R. Guha, R.G. White, J. Li, K.W. Lu, A. Bucceri, T. Zhang, Vehicular communications using dsrc: challenges, enhancements, and evolution, IEEE J. Sel. Areas Commun. 31 (9) (2013) 399–408.
[25] H. Wu, R.M. Fujimoto, G.F. Riley, M. Hunter, Spatial propagation of information in vehicular networks, IEEE Trans. Veh. Technol. 58 (1) (2008) 420–431.
[26] H. Wu, R. Fujimoto, G. Riley, Analytical models for information propagation in vehicle-to-vehicle networks, in: IEEE 60th Vehicular Technology Conference, 2004, VTC2004-Fall, vol. 6, IEEE, 2004, pp. 4548–4552.
[27] M. Liu, J. Naoum-Sawaya, Y. Gu, F. Lecue, R. Shorten, A distributed Markovian parking assist system, IEEE Trans. Intell. Transp. Syst. 20 (6) (2018) 2230–2240.
[28] T. Sanjana, K.A.A. Fuad, M.M. Habib, A.A. Rumel, Automated anti-collision system for automobiles, in: 2017 International Conference on Electrical, Computer and Communication Engineering, ECCE, IEEE, 2017, pp. 866–870.
[29] X. Zhang, Q. Zeng, Q. Meng, Z. Xiong, W. Qian, Design and realization of a mobile seamless navigation and positioning system based on bluetooth technology, in: 2016 IEEE Chinese Guidance, Navigation and Control Conference, CGNCC, IEEE, 2016, pp. 1790–1793.
[30] L. Tijerina, M. Blommer, R. Curry, R. Swaminathan, D.S. Kochhar, W. Talamonti, An exploratory study of driver response to reduced system confidence notifications in automated driving, IEEE Trans. Intell. Veh. 1 (4) (2016) 325–334.
[31] J. Calabuig, J.F. Monserrat, D. Gozalvez, O. Klemp, Safety on the roads: LTE alternatives for sending its messages, IEEE Veh. Technol. Mag. 9 (4) (2014) 61–70.
[32] G. Araniti, C. Campolo, M. Condoluci, A. Iera, A. Molinaro, LTE for vehicular networking: a survey, IEEE Commun. Mag. 51 (5) (2013) 148–157.
[33] E. Yaacoub, F. Filali, A. Abu-Dayya, QoE enhancement of SVC video streaming over vehicular networks using cooperative LTE/802.11 p communications, IEEE J. Sel. Top. Signal Process. 9 (1) (2014) 37–49.
[34] J.A.L. Calvo, R. Mathar, An optimal LTE-V2I-based cooperative communication scheme for vehicular networks, in: 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications, PIMRC, IEEE, 2017, pp. 1–6.
[35] P. Luoto, M. Bennis, P. Pirinen, S. Samarakoon, K. Horneman, M. Latva-Aho, Vehicle clustering for improving enhanced LTE-V2X network performance, in: 2017 European Conference on Networks and Communications, EuCNC, IEEE, 2017, pp. 1–5.
[36] F. Abbas, G. Liu, Z. Khan, K. Zheng, P. Fan, Clustering based resource management scheme for latency and sum rate optimization in V2X networks, in: 2019 IEEE 89th Vehicular Technology Conference, VTC2019-Spring, IEEE, 2019, pp. 1–6.
[37] Y. Horita, R.S. Schwartz, Extended electronic horizon for automated driving, in: 2015 14th International Conference on ITS Telecommunications, ITST, IEEE, 2015, pp. 32–36.
[38] G. T. 36.819, Study on lte-based v2x services, https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2934, 2016.

[39] G. T. 36.885, Study on lte-based vehicle to everything (v2x) services, https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2934, 2015.
[40] S. Kwon, Y. Kim, N.B. Shroff, Analysis of connectivity and capacity in 1-d vehicle-to-vehicle networks, IEEE Trans. Wirel. Commun. 15 (12) (2016) 8182–8194.
[41] W. Chen, I. Ahmad, K. Chang, Co-channel interference management using eicic/feicic with coordinated scheduling for the coexistence of PS-LTE and LTE-R networks, EURASIP J. Wirel. Commun. Netw. 2017 (1) (2017) 34.
[42] J.-G. Choi, S. Bahk, Cell-throughput analysis of the proportional fair scheduler in the single-cell environment, IEEE Trans. Veh. Technol. 56 (2) (2007) 766–778.
[43] Z. Hanzaz, H.D. Schotten, Analysis of effective sinr mapping models for mimo ofdm in LTE system, in: 2013 9th International Wireless Communications and Mobile Computing Conference, IWCMC, IEEE, 2013, pp. 1509–1515.
[44] S. Sesia, I. Toufik, M. Baker, LTE-the UMTS Long Term Evolution: From Theory to Practice, John Wiley & Sons, 2011.
[45] G. Fodor, C. Koutsimanis, A. Rácz, N. Reider, A. Simonsson, W. Müller, Inter-cell interference coordination in ofdma networks and in the 3GPP long term evolution system, J. Commun. 4 (7) (2009) 445–453.
[46] A.S. Hamza, S.S. Khalifa, H.S. Hamza, K. Elsayed, A survey on inter-cell interference coordination techniques in ofdma-based cellular networks, IEEE Commun. Surv. Tutor. 15 (4) (2013) 1642–1670.
[47] M. Rahman, H. Yanikomeroglu, Enhancing cell-edge performance: a downlink dynamic interference avoidance scheme with inter-cell coordination, IEEE Trans. Wirel. Commun. 9 (4) (2010) 1414–1425.
[48] S. Zhang, Inter-cell interference coordination in indoor LTE systems, 2011.
[49] F. Khan, LTE for 4G Mobile Broadband: Air Interface Technologies and Performance, Cambridge University Press, 2009.
[50] M.E. Sahin, I. Guvenc, M.-R. Jeong, H. Arslan, Handling CCI and ICI in OFDMA femtocell networks through frequency scheduling, IEEE Trans. Consum. Electron. 55 (4) (2009) 1936–1944.
[51] S. Park, W. Seo, Y. Kim, S. Lim, D. Hong, Beam subset selection strategy for interference reduction in two-tier femtocell networks, IEEE Trans. Wirel. Commun. 9 (11) (2010) 3440–3449.
[52] A. Anpalagan, M. Bennis, R. Vannithamby, Design and Deployment of Small Cell Networks, Cambridge University Press, 2015.
[53] A. Masmoudi, S. Feki, K. Mnif, F. Zarai, Efficient radio resource management for D2D-based LTE-V2X communications, in: 2018 IEEE/ACS 15th International Conference on Computer Systems and Applications, AICCSA, IEEE, 2018, pp. 1–6.
[54] H.D.R. Albonda, J. Pérez-Romero, An efficient ran slicing strategy for a heterogeneous network with embb and V2X services, IEEE Access 7 (2019) 44771–44782.
[55] Z. Kaleem, B. Hui, K. Chang, QoS priority-based dynamic frequency band allocation algorithm for load balancing and interference avoidance in 3GPP LTE hetnet, EURASIP J. Wirel. Commun. Netw. 2014 (1) (2014) 185.
[56] M. Hossain, A. Ashiq, M.S. Ifthekhar, M.N. Uddin, Y. Jang, Interference reduction mechanism for fractional frequency reuse in hybrid wireless network, in: 2017 International Conference on Information and Communication Technology Convergence, ICTC, IEEE, 2017, pp. 208–212.
[57] S. Alotaibi, R. Akl, Dynamic fractional frequency reuse (FFR) scheme for two-tier network in LTE, in: 2017 IEEE 8th Annual Ubiquitous Computing, Electronics and Mobile Communication Conference, UEMCON, IEEE, 2017, pp. 408–413.
[58] G. T. 2010, Mobile broadband innovation path to 4G: Release 9, 10 and beyond, February 2010, 3GPP, TR.
[59] E. Pateromichelakis, M. Shariat, A. ul Quddus, R. Tafazolli, On the evolution of multi-cell scheduling in 3GPP LTE/LTE-A, IEEE Commun. Surv. Tutor. 15 (2) (2012) 701–717.
[60] E.T. Tiirola, K.J. Hooli, J.Y. Hulkkonen, K.P. Pajukoski, Signalling a muting pattern to a user equipment for time domain enhanced inter-cell interference coordination, Dec. 26, 2013.
[61] P. Gaal, T. Luo, W. Chen, J. Montojo, Interaction of PDSCH resource mapping, CSI-RS, and muting, US Patent 9,130,725 (Sep. 8 2015).
[62] V. Chandrasekhar, R. Chen, Multi-cell signaling of channel state information-reference signal and physical downlink shared channel muting, uS Patent 8,750,887 (Jun. 10 2014).
[63] J. Wang, X. Yun, S. Nagata, L. Chen, Investigation on CQI definition for CoMP in LTE-advanced downlink, in: 2013 IEEE 77th Vehicular Technology Conference, VTC Spring, IEEE, 2013, pp. 1–5.
[64] S. Scholz, Combining dynamic clustering and scheduling for coordinated multipoint transmission in LTE, in: 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications, PIMRC, IEEE, 2017, pp. 1–7.
[65] I. Ahmad, W. Chen, K. Chang, LTE-railway user priority-based cooperative resource allocation schemes for coexisting public safety and railway networks, IEEE Access 5 (2017) 7985–8000.