Chapter

An LTE-Direct-Based Communication System for Safety Services in Vehicular Networks

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Abstract

With the expected introduction of fully autonomous vehicles, the long-term evolution (LTE)-based vehicle-to-everything (V2X) networking approach is gaining a lot of industry attention, to develop new strategies to enhance safety and telematics features. The vehicular and wireless industries are currently considering the development of an LTE-based system, which may co-exist, with the IEEE 802.11p-based systems for some time. In light of the above fact, our objective is to investigate the development of LTE Proximity Service (ProSe)-based V2X architecture for time-critical vehicular safety applications in an efficient and cost-effective manner. In this chapter, we present a new cluster-based LTE sidelink-based vehicle-to-vehicle (V2V) multicast/broadcast architecture to satisfy the latency and reliability requirements of V2V safety applications. Our proposed architecture combines a new ProSe discovery mechanism for sidelink peer discovery and a cluster-based round-robin scheduling technique to distribute the sidelink radio resources among the cluster members. Utilizing an OMNET++ based simulation model, the performance of the proposed network architecture is examined. Results of the simulation show that the proposed algorithms diminish the end-to-end delay and overhead signaling as well as improve the data packet delivery ratio (DPDR) compared with the existing 3GPP ProSe vehicle safety application technique.

Keywords: clustering, D2D, LTE, proximity services, resource allocation, safety applications, vehicular ad hoc network, V2V, V2X

1. Introduction

A vehicular communication system is one of the key components of intelligent transportation and traffic management systems. Advanced traffic management systems are expected to improve traffic flow, reduce congestions and accidents, and optimize the energy consumption of vehicles. Vehicular communication systems should enable just in time data exchange mechanisms among different elements of traffic management. Early versions of the vehicular networks were developed primarily to support V2V communications which are now evolving to vehicle-to-everything (V2X) communications mode [1]. A V2V system enables vehicles to exchange messages within the close vicinity of a Host Vehicle (HV), whereas the V2X service enables the vehicle to exchange information among any data devices in the vehicular network or in the infrastructure network. The enhanced features of vehicular networks are increasing the need for more flexible communication network architecture that can support diversified services, from time-critical safety services to high data rate entertainment services. The time-critical safety services are key features of the vehicular networks to reduce traffic accidents and offer better road safety services. Hence the role of the communication network will be crucial in a vehicular network.

The vehicular ad hoc network (VANET) architecture was initially developed using the dedicated short-range communication (DSRC) and the IEEE 802.11p networking standards [2]. The main objective of the VANET is to support V2V and vehicle-to-infrastructure (V2I) communication modes. The IEEE 802.11p network uses the random-access medium access control protocol carrier-sense multiple access with collision avoidance (CSMA/CA) to support V2V and V2I services. The advantages of the CSMA/CA protocol are in its simplicity, minimum control signaling, and the broadcast nature of transmission. These enable low packet transmission delay at lower teletraffic load. However, due to the lack of coordination among transmitters, packet collisions can occur which can increase the packet transmission delay as well as reduce the packet delivery ratio. Also, the performance of an IEEE 802.11p network is affected by the network node densities which could vary on roads depending on the road layout, congestions, and time of the day. Hence the main bottlenecks of an IEEE 802.11p vehicular network are the scalability and lack of adequate Quality of Service (QoS) support for a different class of services. However, the IEEE 802.11p standard-based vehicular network technology has matured, and many commercial products are now available [3, 4]. With the introduction of 5G technologies, the transportation and ICT industries have refocused their attention to developing new systems and products mainly relying on the Long Term Evolution (LTE)-based technologies [5].

The LTE standard is commonly used as the 4G broadband wireless technology which is further evolving as one of the major components of the 5G technology [6]. The LTE is a wide-area wireless networking technology standard that uses the conventional cellular network architecture and uses direct radio communication between the user equipment (UE) and the base station commonly known as the eNodeB (eNB) as shown in **Figure 1**. The Enhanced UMTS Terrestrial Radio Access Network (E-UTRAN) represents the radio access network where the eNB and user equipment (UE) are located. The Evolved Packet Core Network (EPC) connects the radio access networks and the external network such as the Internet. The core network hosts various control entities, databases, and functional servers. Cellular networks have several benefits such as wide-area coverage, high data rate, and guaranteed QoS for multiple services. However, the conventional centralized cellular networks are not always suitable for vehicular networks to support some of the services particularly for distributing time-sensitive broadcast services such as the Cooperative Awareness Message (CAM). In a conventional cellular network, all data communication between devices must go through the eNB, irrespective of whether they are located next to each other or at a long distance. The CAMs are transmitted from each vehicle to its neighboring vehicles to distribute situational awareness information.

The CAMs are periodic messages that have a 10 Hz generation frequency with latency restrictions of 100 ms. In the 802.11p-based VANET, the CAM messages are broadcasted to the neighboring vehicles using the CSMA/CA protocol. Generally, conventional cellular networks can support unicast, broadcast, and multicast communications; however, these configurations are not suitable for the CAM message transmissions due to high signaling overhead. To accommodate the needs of vehicular networks, the 3GPP has started to standardize the LTE-V standard to

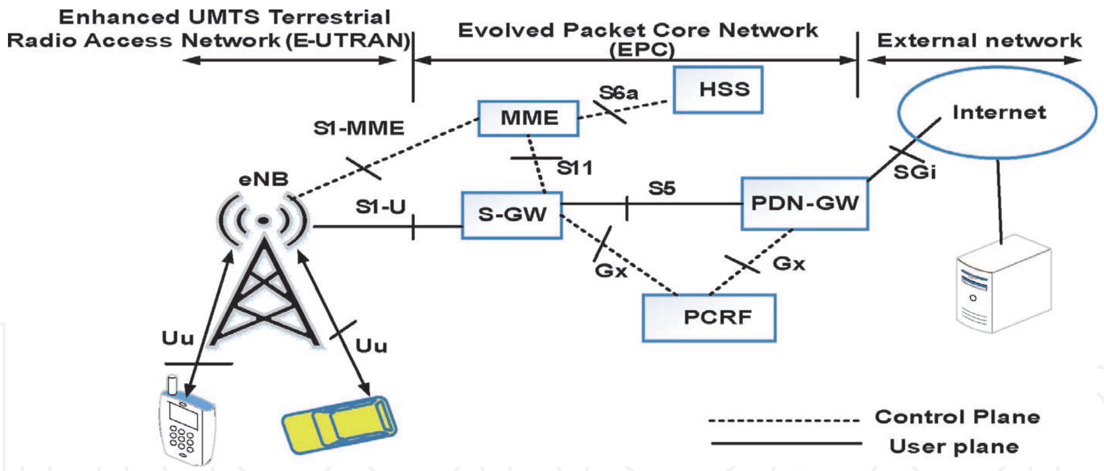

Figure 1.
LTE network architecture.

support V2X services which encompass three modes of communications: V2V, V2I, and vehicle-to-pedestrian (V2P) in Release 14. To support vehicular networking requirements, the standard has developed a new channel architecture using the PC5 interface. The standard also supports the conventional Uu interface for different vehicular services. The PC5 interface includes the sidelink which has D2D communication abilities developed under Release 12 of the LTE standard. Release 12 was mainly developed for public safety applications. The V2X communication services are being enhanced in the LTE Release 15 and will be further enhanced in Release 16.

In this chapter, we firstly review the vehicular networking and service requirements. Following the review of networking and service requirements, we briefly review the LTE-V/LTE-V2X standard. The discussion then focuses on our new algorithm referred to as Cluster-Based Cellular Vehicle-to-Vehicle (CBC-V2V) combined with a new peer discovery model referred to as Evolved Packet Core Level Sidelink Peer Discovery (ESPD). The chapter also presents the performance analysis of the CBC-V2V algorithm and compares the performance of the algorithm with other standard algorithms. In Section 2, we present the review on future vehicular network requirements. In Section 3, we briefly introduce the LTE-V/VX standard. In Section 4, our proposed LTE standard-based vehicular network resource allocation algorithm is presented. In Section 5, we present the simulation model developed to analyze the performance of the CBC-V2V algorithm. Conclusions are drawn in Section 6.

2. Future vehicular network requirements

Traffic management systems are constantly evolving to improve road traffic services and the safety of road users. Recently, the 3GPP introduced a number of vehicular network use cases in the LTE-V2V Release 14 [7] for future vehicular networks. The study showed that the vehicular network requirements have evolved over time. In early days, vehicular networks were developed mainly to support safer vehicle movements and reduce traffic congestion. However, future vehicular networks are planning to support a range of basic and enhanced services. Some of the future suggested services are listed below. The following list shows that future vehicular network requirements have been extended to include several smart city services such as parking management services, pedestrian and vulnerable road user safety. These services need to be supported by four different network configurations, i.e., V2V, V2I, V2P, and Vehicle-to-Network (V2N). Some of the service characteristics are briefly summarized in **Table 1**.

- Forward collision warning (FCW)
- Control loss warning (CLW)
- Emergency vehicle warning
- V2V emergency stop
- Cooperative Adaptive Cruise Control (CACC)
- V2I emergency stop case
- Queue warning
- Road safety services
- Automated parking system (APS)
- Wrong-way driving warning (WDW)
- V2X message transfer
- Pre-crash sensing warning
- V2X services in areas outside network coverage
- V2X road safety services via infrastructure
- V2N traffic flow optimization
- Curve speed warning
- Warning to pedestrian messaging
- Vulnerable road user (VRU) safety

Table 1 shows that communication needs and service requirements of future vehicular networks are quite diverse with variable QoS requirements. It is expected that over time, the service categories will grow, and their requirements will evolve. To support the above multiservice requirements, the current IEEE 802.11p networks will not be adequate due to higher traffic volume and inadequate QoS support for multiservice networks. Also, some of the services such as emergency vehicle warning or curve speed warning may need longer transmission ranges and may also increase the collision probability in CSMA/CA-based IEEE 802.11p networks. Another important consideration for the future vehicular network is the support of autonomous vehicles that require low delay and low loss reliable communication networks. Hence, the main objective of the LTE-V/LTE-V2X standard is developing an advanced cellular-based vehicular network. In the following section, we review the LTE-V2X standard based on Release 14.

Service	Main purpose	Communication mode	Service requirements
Forward collision warning	The FCW service has been proposed to warn the driver of a host vehicle (HV) about an impending rear end collision with a remote vehicle (RV) or vehicles. The FCW service can help reduce collisions	HV and RV communicate using V2V transmission mode	Periodic broadcast CAM message, support high mobility, early warning message
Control loss warning	The CLW service enables an HV to broadcast self-generated loss of control message to RVs. Upon receiving the message, RVs warn drivers for appropriate action(s)	HV and RV communication using V2V services	Communicate messages over a distance to generate warning message with ample time to respond. Event-based broadcast message
Emergency vehicle warning	This service enables all vehicles to acquire location, speed, and direction information of surrounding emergency vehicle(s) to assist smooth movement of emergency vehicles	V2V communication using LTE-D2D	Event-based CAM message broadcast to cars within 300–500 meters
Cooperative Adaptive Cruise Control (CACC)	The CACC service provides convenience and safety benefits to group of vehicles in close vicinity. Can be used for platooning structure	Mainly V2V services, but V2X communication can also be used to obtain forward traffic flow information	The service can support a maximum latency of 1 sec and a maximum frequency of one message per second
Queue warning	This service allows vehicles to receive forward road queue warning messages. Road user safety can be significantly increased by using this service	V2V and V2I communication services	Able to transmit and receive V2I messages with a maximum relative velocity of 160 km/h. Support an appropriate communication range necessary for early warning
Road safety services	Using this service, V2X messages are delivered from an UE to other UEs via an installed Road Side Unit.	V2X and V2I services	A V2X message should be delivered within 100 ms via an RSU with low delivery loss. An RSU should be able to transmit V2X messages at a maximum frequency of 10 Hz
Curve speed warning	This application sends alert messages to the driver to manage possible blind spot or the curve at an appropriate speed. An RSU is placed before a curve to transmit information such as curve location, recommended speed, curvature, and road surface conditions	RSU-based I2V and V2I services	I2V message transmission with a maximum latency of 1 sec and maximum frequency of one message per second

Table 1.
Service characteristics.

3. LTE-V2X standard

The LTE standard is widely used in public and private mobile radio networks. LTE technology has been identified to support vehicular network services using V2X architecture. The V2X service architecture is shown in **Figure 2**. As mentioned in the previous section, the V2X communication services include four different modes of communication (V2V, V2I, V2P, and V2N). These links are bidirectional. 3GPP study groups in collaboration with transport industries have started standardization activities on LTE-based vehicular networks in the working group 1. After several studies and developing several initial specifications on V2X services based on LTE, Release 14 was published in 2017 [8]. The standard is further developed in Release 15 in 2018 supporting enhanced V2X networking features. The enhancements go beyond the support of CAM and Decentralized Environmental Notification Messages (DENM) transmissions as shown in **Table 1**. The 3GPP specifications did not allocate any specific frequency band to support V2X services. European Telecommunications Standard Institute (ETSI) has allocated a 70 MHz spectrum in the 5.9 GHz band in which there is no overlap between V2X and conventional cellular network services. This separation of operating frequency will enable different operators to provide vehicular network services independent of conventional mobile operators. The 5.9 GHz LTE band will allow the system to coexist with IEEE 802.11p-based systems. However, the mobile operators can also use the licensed band to support the V2X services. The V2X services can use the conventional air interface as well as the newly developed D2D interface using the sidelink channel. The D2D communication architecture is briefly introduced in the following section.

3.1 D2D communication architecture

The LTE-V2X architecture has been developed to support diverse vehicular network services as discussed above. The architecture uses the new air interface PC5 along with the conventional Uu interface to support various services. The PC5 interface can offer enhanced network services such as device-to-device communication, normally supported by the ad hoc network architecture. The device-to-device communication services was introduced in Release 12 which was originally developed for the safety services [9]. The LTE Release 12 architecture is shown in **Figure 3**. The figure shows a new service function the Proximity Service located in the Evolved Packet Core which allows the devices to discover peer devices for D2D

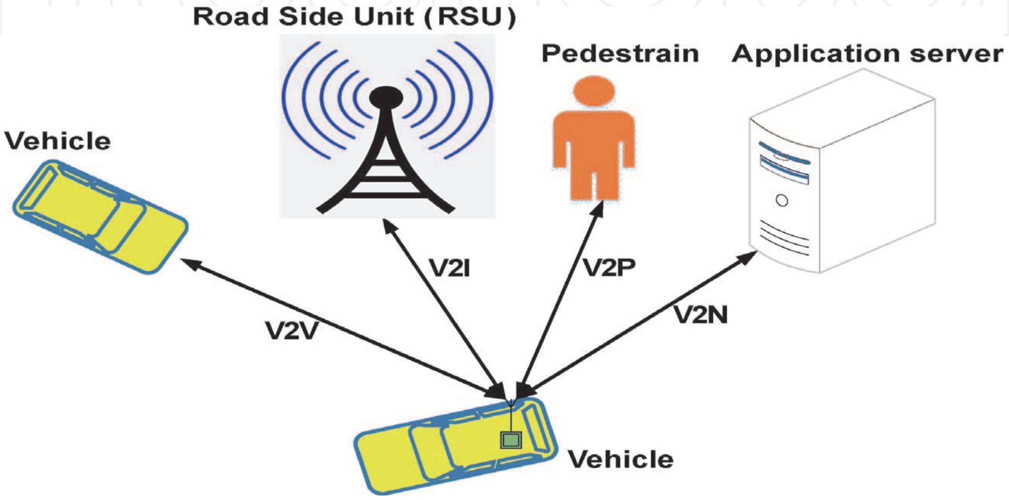

Figure 2.
V2X communication architecture.

communication services. The ProSe function allows users to directly communicate and exchange data with neighboring devices by sending a registration message to the eNB with a ProSe application ID. The eNB organizes the communication between the devices using the control channels. Once the communicating devices are matched by the eNB, then they can directly communicate using the PC5 interface as shown in **Figure 3**. The PC interface functions are summarized in **Table 2**. Details of these interfaces can be found in [10].

The channels in the Uu and PC5 interfaces are organized as logical, transport, and physical channels. **Figure 4** shows the mapping structure of these channels used for the sidelink communication in the LTE standard. There are two logical channels introduced for sidelink communication: first is the SL Traffic Channel (STCH), and second is SL Broadcast Control Channel (SBCCH). The STCH is an interface to the Physical SL shared Channel (PSSCH), which transports the data carrying user information over the air. The SBCCH is used to broadcast control data, for synchronization in the out of coverage or partial coverage, or for the synchronization between UEs which are located in different cells. There is also a Transport and Physical Sidelink Control Channel carrying the SL control information (SCI). There is a new transport and physical channel for direct discovery: sidelink discovery channel (SL-DCH) and the physical sidelink discovery channel (PSDCH).

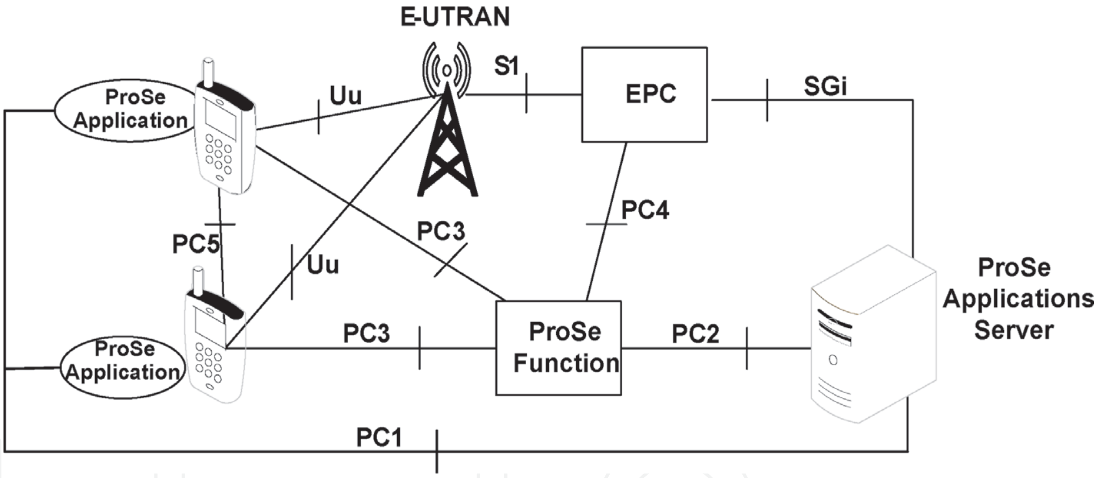

Figure 3.
LTE release 12 D2D reference network architecture [9].

Interface	Main functions
PC1	The ProSe application server can communicate towards a ProSe application in the UE through the interface
PC2	The ProSe application server can communicate with the ProSe function through this interface
PC3	The ProSe function can connect to the UE through the PC3 interface
PC4	The ProSe function connects with Evolved Packet Core in the network through PC4 interface
PC5	A PC5 interface enables direct communication between two UEs

Table 2.
PC interfaces.

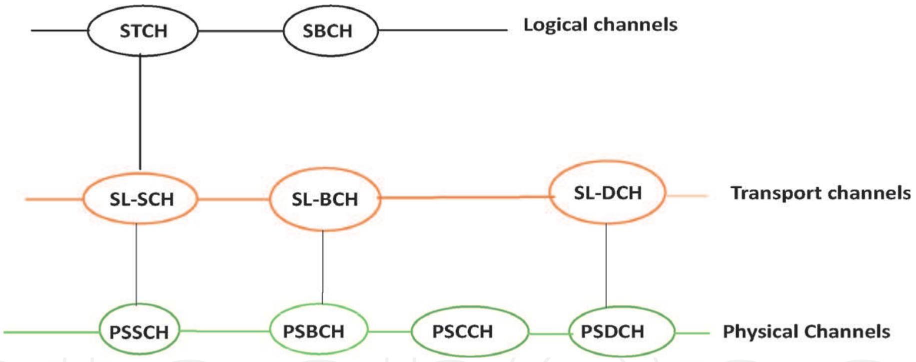

Figure 4.
Mapping of channels for sidelink communication in 3GPP LTE.

3.2 Enhanced D2D communication architecture for V2X communications

Recently, several fundamental modifications have been carried out to enhance the PC 5 interface in the Release 14 to support V2X operational scenarios and requirements as shown in **Table 1** [11]. The sidelink LTE-V2X employs the single-carrier frequency division multiple access (SC-FDMA) which permits the UE to access radio resources in both time and frequency domains. In the frequency domain, the subcarrier spacing is fixed to 15 kHz, and subcarriers are utilized in groups of 12 (i.e., 180 kHz). To support different V2X operational requirements, the transmission channels may use a higher carrier frequency of 6 GHz with very high relative velocity. However, due to the high relative velocity and the use of higher carrier frequency, inter-carrier interference (ICI) due to higher Doppler shift and insufficient channel estimation due to shorter coherence time could be a problem compared to the legacy 3GPP systems.

To improve the performance in the presence of high Doppler shift, the sidelink interface has been tuned to counteract the severe Doppler shift experienced at high speed. In the time domain, additional demodulation reference signal (DMRS) symbols have been added in one subframe to handle the high Doppler shift associated with relative speeds of up to 500 km/h and the use of higher carrier frequency [13]. The new subframe structure is illustrated in **Figure 5**. Fourteen symbols form a subframe of 1 ms, also called transmission time interval (TTI), which include nine data symbols, four demodulation reference signal (DMRS) symbols, and one empty symbol for Tx-Rx switch and timing adjustment. The LTE-V2X has a large number of modulation and coding schemes (MCS), with 4-QAM and 16-QAM modulations, and an almost continuous coding rate. The minimum radio resource allocated to an

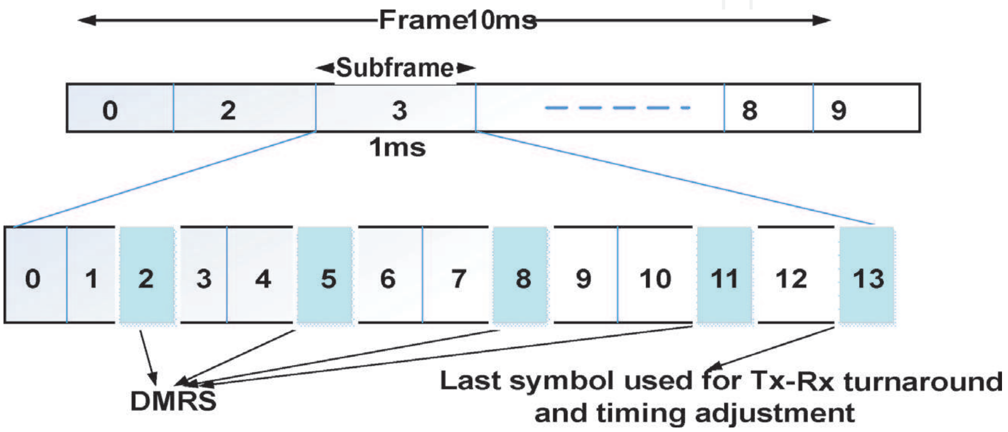

Figure 5.
V2V subframe for PC-5 interface structure [13].

LTE-V2X link is the subchannel in the frequency domain, corresponding to a multiple of the 12 subcarriers groups, and the TTI in the time domain. One packet normally occupies one or more subchannels in a TTI. To improve the system-level performance under high node density while meeting the latency requirement of a V2V link, a new classification of scheduling assignment and data resources is designed where the scheduling assignment is transmitted in sub-channel using specific Resource Blocks (RBs) across the time. More specifically, each data packet also known as Transport Block (TB) has an associated control message called the Sidelink control information (SCI). TB and the associated SCI must be transmitted in the same subframe but can be allocated in adjacent and nonadjacent resource blocks.

Figure 6 depicts the overall network architecture enhancement in Release 16 for V2X services [14]. Two new entities are introduced: the V2X Application server and the V2X control function to support the V2X services. The V2X control function is the logical function that is used for network-related actions required for V2X. The parameters required for V2X communications can be obtained from V2X Application Server. It is also provision the UEs with Public Land Mobile Network (PLMN) specific parameters that allow the UE to use V2X in this specific PLMN. The V2X Application server incorporates the V2X capability for building the application functionality. It is responsible for receiving uplink data from the UE in the unicast mode, providing the parameters for V2X communications over the PC5 reference point to V2X control function. As per the network architecture, several new reference points (or interface) have been introduced. The roles of V2X reference points are summarized in **Table 3**.

To support the V2X communication, Release 14 introduced the new communication modes (mode 3 and mode 4) as shown in **Figure 7**. Mode 1 from Release 12 was enhanced to mode 3 for V2X communication; similarly, mode 2 from D2D was enhanced to mode 4 for V2X. In mode 3, the UEs' resource reservation and scheduling are performed by the eNB, while in mode 4 the UEs choose the radio resources autonomously. Mode 3 algorithms are not defined in the specifications and their implementation is left to vendors. In contrast, mode 4 can operate without cellular coverage and is therefore considered as the baseline V2V mode since safety applications cannot always depend on the availability of cellular coverage. In mode 4, also known as autonomous or out-of-coverage, each node selects the resources based on a sensing procedure and a semi-persistent scheduling (SPS) mechanism. Mode 4 includes a distributed scheduling scheme for vehicles to select their radio resources and includes the support for distributed congestion control. The detailed

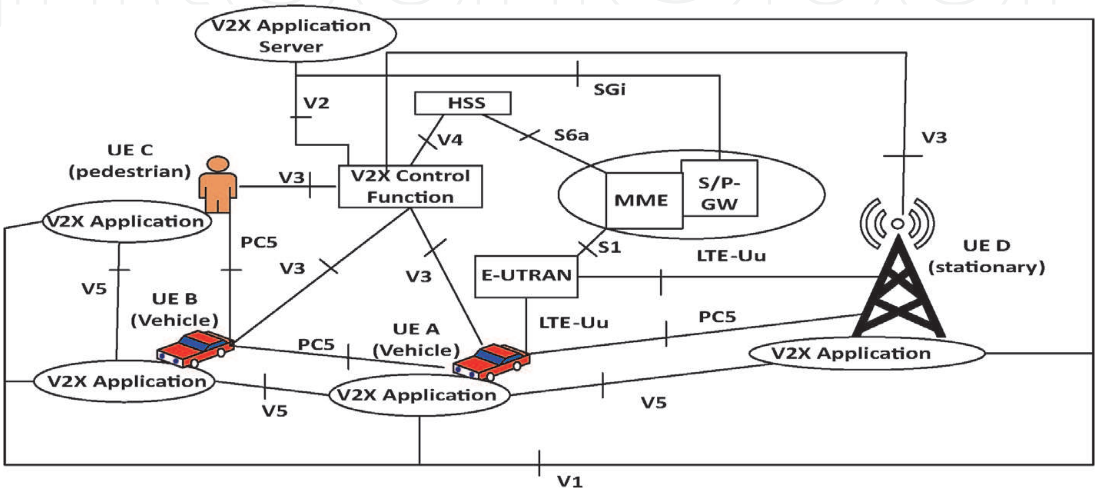

Figure 6.
Enhanced ProSe D2D sidelink architecture for V2X communications [14].

Interface	Main functions
V1	The V2X application server can communicate towards an V2X application in the UE through V1 interface
V2	The V2X application server can communicate with the V2X control function through V2 interface. The V2X application server may connect to V2X control function belonging to multiple PLMNs
V3	The V2X control function can connect to the UE through the V3 interface
V4	The V2X control function connects with entity Home Subscriber Server (HSS) in Evolved Packet Core in the 3GPP network through V4 interface
V5	A V2X application in UE can communicate towards a V2X application in different UEs through V5 interface
SGi	An EPC can connect to the V2X application server through SGi interface

Table 3.
V2X interfaces.

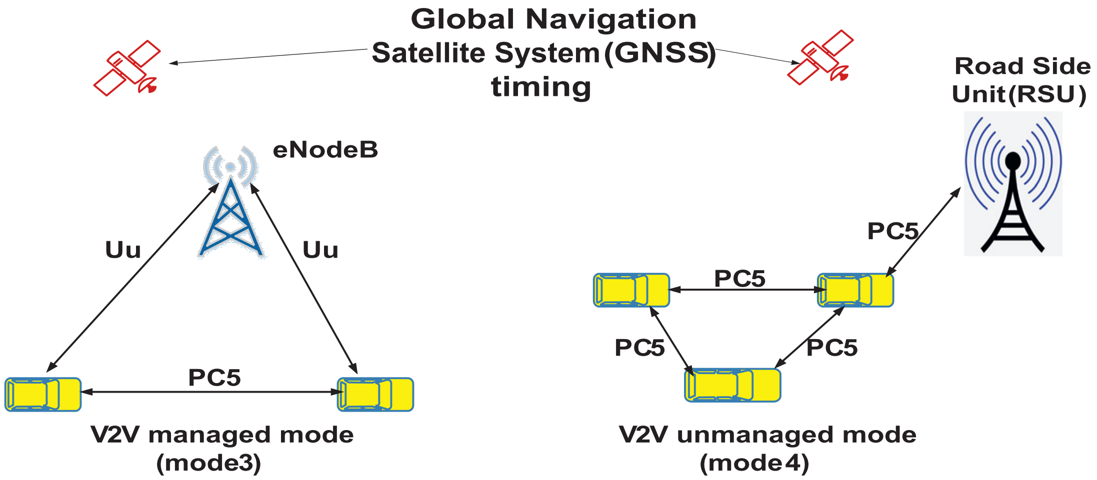

Figure 7.
V2X communication mode defined in release 14.

description by 3GPP for mode 4 algorithm is presented in [12, 15]. The Global Navigation Satellite System (GNSS) is introduced to provide accurate timing and frequency references in the off-coverage scenario [16].

3.3 Review on current research on LTE vehicular networks

Since the LTE Release 14 was standardized, several studies have been carried out to compare the performance of IEEE 802.11p and LTE-V2X vehicular networks. In [17], comparative experiments with real devices were carried out, demonstrating improvement of the C-V2X system performance. The work demonstrated that the latency in C-V2X under congested conditions can be maintained under 100 ms.

The use of cellular technologies for vehicular networks has been investigated to meet the requirements of safety services in [5, 18, 19]. The work showed that traffic hazard warning messages are disseminated in less than a second. Hybrid architectures based on the LTE and the 802.11p standards have been proposed to exploit the benefits of both networks [20, 21]. Sivaraj et al. [20] present a cluster-based centralized vehicular network architecture which uses both the 802.11p and the LTE standards for well-known urban sensing application and floating car data (FCD) application. The authors also compared those system performances with other decentralized clustering protocols. Remy et al. [21] propose a cluster-based VANET-LTE hybrid architecture for multimedia-communication services.

In [22], the authors provide the delay performance analysis of hybrid architectures. Calabuig et al. [22] propose a hybrid architecture known as the VMaSC-LTE that integrates the LTE network with the IEEE 802.11p-based VANET network. In [22], the authors propose a Hybrid Cellular-VANET Configuration (HCVC) to distribute road hazard warning (RHW) messages to distant vehicles. In this hybrid architecture, cluster members (CMs) communicate with the cluster head (CH) by using the IEEE 802.11p link, and the CHs communicate with the eNB by using cellular links. However, this proposed 802.11p-LTE hybrid architecture increases the transmission delay at the same time as reducing the reliability when the IEEE 802.11p-based network needs to support higher node densities, leading to higher medium access delays. Toukabri et al. [23] propose a Cellular Vehicular Network (CVN) solution as a reliable and scalable operator-assisted opportunistic architecture that supports hyper-local ITS services for the 3GPP Proximity Services. A hybrid clustering approach is suggested to form a dynamic and flexible cluster managed locally by the ProSe-CHs. However, the authors do not focus on the transmission of safety messages in the network.

In [24–26], the authors compare the performance of the IEEE 802.11p and the LTE-V2X in terms of reliability. They mainly used simulation with a moving vehicle and consider the highway scenario to analyze the performance of two technologies. Some of them also include an urban Manhattan case [25, 26]. Bazzi et al. [27] compare IEEE 802.11p and LTE-V2V for cooperative awareness in terms of maximum awareness range and also provides analytical evaluation of the proposed schemes. Min et al. [25] introduce a resource scheduling algorithm known as Maximum Reuse Distance (MRD) for V2V communication under network coverage. The proposed scheduling algorithm is in-line with Cellular-V2X mode 3 with the aim of minimizing the interference and increasing the reliability and latency of V2V communication.

Recently, a global alliance called the Fifth Generation Automotive Association (5GAA) has developed a model to assess the relative performance of LTE-V2X (PC5) and the IEEE 802.11p technologies with regard to improving the safety, focusing on direct communications [28]. This study indicates that the LTE-V2X (PC5) outperforms the 802.11p in reducing fatalities and serious injuries on European roads. All of the abovementioned works agree that LTE-V2X can provide better performance compare to IEEE 802.11p. This is due to a combination of the superior performance of LTE-V2X (PC5) at the radio link level for ad hoc/direct communications between road users. However, the use of LTE-V2X for vehicular applications is not mature yet. In particular, LTE-V2V devices are still under development, and the allocation (and management) of radio resources is still under investigation.

4. CBC-V2V system model

In this section, we present an LTE-based cellular network architecture for V2X communication using the PC5 interface of the LTE standard. We assume that all vehicles on the road are within the coverage of the eNB. A highway road traffic scenario is considered where traffic is flowing in both directions in a multilane road as depicted in **Figure 8**. We assume that each vehicle is equipped with a GPS device capable of providing accurate position measurements. The highway is partitioned into fixed-size regions known as a cluster. Vehicles on the road with near

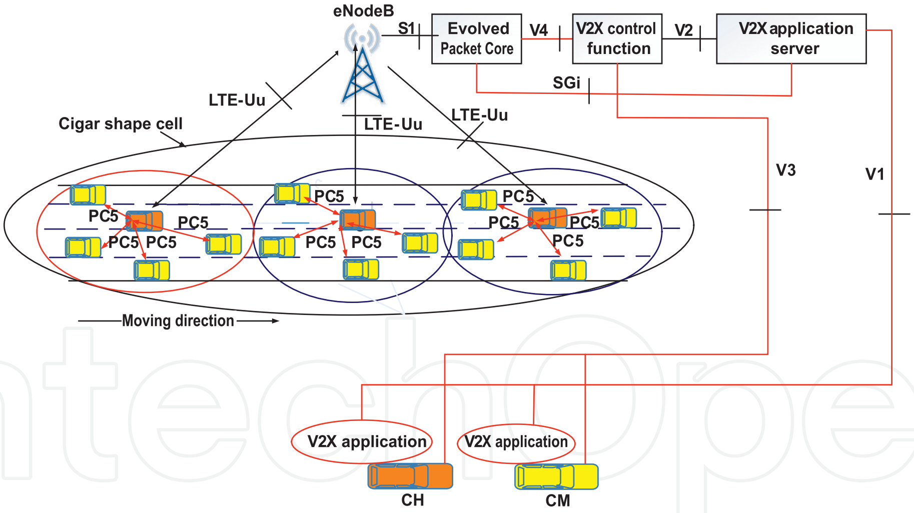

Figure 8.
Highway scenario for proposed cluster-based V2V cellular (CBC-V2V) architecture.

proximities form a cluster where they exchange the safety messages to each other using a CBC-V2V-based packet transmission technique.

We are considering two types of vehicles: the first type represents the user terminals capable of acting as a CH and supports D2D communication using the PC5 interface. The CH also manages the network resource usage among the group of devices communicating over D2D links. The second type of vehicles represents the network devices that can only act as CMs. These vehicles connect to the appropriate CH to assist them in establishing the D2D links to exchange messages. In this model, a vehicle uses two communication links: the conventional Uu channels and the D2D links using the PC5 interface. Cluster members can communicate with others using the PC5 links, whereas a CH communicates with the eNB using the Uu interface. Although the D2D channels enable two neighboring UEs to communicate directly, all signaling and data transmission processes should still be under the control of the eNB in order to comply with the LTE-Advanced architecture requirements.

4.1 Cluster-based cellular V2V (CBC-V2V) communication architecture

We propose a cluster-based cellular V2V communication architecture that combines the new sidelink peer discovery model to support safety services. We propose to use a cluster topology where communication among cluster members is coordinated by the cluster shown in **Figure 8**. Vehicular networks are generally dynamic where vehicles may arrive new in a cluster location or may leave a cluster. For a newly arrived vehicle, it is necessary to find out necessary system information to join an appropriate cluster. In the following section, our proposed sidelink peer discovery model is presented. Following that discussion, our cluster-based cellular V2V communication mechanism combining with a round-robin scheduling technique is proposed to distribute the radio resources among the cluster nodes.

4.2 EPC level sidelink peer discovery (ESPD) model

For direct communication, two devices must be aware of each other. ProSe peer discovery is the first step to start a direct transmission. Since the introduction of D2D communication architecture in Release 12, many device/peer discovery techniques have been developed using two models defined in the standard. From the user's perspective, they can be classified into restricted discovery and open discovery [29]. For restricted discovery, the user entity is not allowed to be detected without its explicit permission. In this case, it prevents other users to distribute their information to protect user privacy. It suits social network applications (e.g., group gaming and context sharing with friends). For open discovery, a user entity can be detected as long as it is within another device's proximity. From the network's perspective, device discovery can be divided into two types: direct discovery and Evolved Packet Core (EPC) discovery. UE would search for a nearby device autonomously; this requires a UE device to participate in the device discovery process. Direct discovery work in both in-coverage and out-of-coverage scenarios. There are also provisions for EPC level discovery that notifies the terminal about other users detected in the vicinity based on the user interest information and the UE location information registered by terminals in the ProSe function [30].

All vehicles that need to use the D2D link must have the ProSe capability features: the ability to discover, to be discovered, and to communicate with discovered devices. Within the existing EPC level discovery model, the ProSe function authenticates the user by checking its credential with the HSS as to whether the user is permitted to utilize ProSe features. After successful authentication of the UE, the ProSe function creates an EPC ProSe Subscriber ID (EPUID) and assigned it to the registered device. Once a vehicle registered as a ProSe subscriber, it can run the applications that support proximity services, named as a ProSe-enabled applications. The application server allocates the user an Application Layer User ID (ALUID) to recognize him within the context of this particular application.

However, these device discovery and the EPC level discovery models require significant control signaling or message exchanges such as announce requests, monitor requests, match reports, etc. [30, 31]. Our proposed discovery mechanism diminishes network resource requirements. It assumes that every vehicle is equipped with a GPS receiver and can accurately determine its position and direction of movement. **Figure 9** appears the signaling diagram of the proposed EPC level discovery technique elaborated as follows:

1. When a new vehicle reaches an eNB coverage area, the downlink frame synchronization is accomplished once it has decoded the primary synchronization signal (PSS) and the secondary synchronization signal (SSS) messages, which are accessible on the downlink broadcast control channel. The

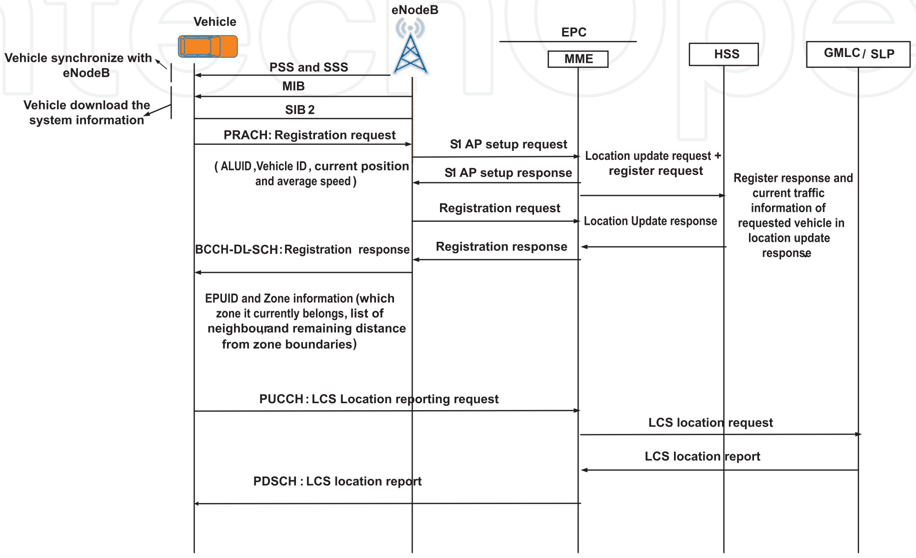

Figure 9.
EPC level Sidelink peer discovery (ESPD) model for VANET.

vehicle at that point downloads the Master Information Block (MIB) from the broadcast channel. This channel incorporates the downlink and uplink carrier configuration information. Further, the vehicle utilizes the Downlink Shared Channel (DL-SCH) to download the system information block. The SIB2 block contains necessary parameters for the initial access transmission.

2. In the initial state, each vehicle on the road must register itself with the eNodeB using its current GPS position. Unlike the existing EPC level discovery, the vehicle sends its location information in the registration request to the eNodeB instead of using the ProSe function for user (vehicle) registration. The vehicles will forward their information (such as ALU_ID, current GPS location, an average speed of the vehicle, discovery range, and vehicle ID) in the registration request message utilizing the Random Access Channel (RACH) to the eNB. The eNB acknowledges the registration request and broadcasts the registration response back to vehicles along with the current traffic profile over the broadcast channel. The vehicle's traffic profile contains an EPC ProSe Subscriber ID, zone information (i.e., to which zone it currently belongs), neighboring vehicle list, and the vehicle's remaining distance from its location.

3. After accepting the information supplied in the registration response, the vehicle collects all the data in its Vehicle Information Register (VIR), a repository that stores vehicle and surrounding information. For D2D communication, each vehicle updates its neighborhood table with a new list of neighboring vehicles and builds knowledge of its local environment. The global mobile location center (GMLC) keeps vehicle locations tracked. Once the vehicle comes to a new zone or crosses the boundary of the zone, the location alert, i.e., the Location Service (LCS) report, will be received and vehicle will require re-registration to update its VIR.

4.3 Cluster formation

After the peer discovery, each vehicle needs to select an appropriate Cluster Head (CH) to associate with it. Using the peer discovery model, after successful registration, each vehicle updates its Neighborhood Table (NVT) in its VIR with the new proximity data (i.e., a list of neighbor vehicles) along with the vehicle ID, total number of vehicles, and current state of the each vehicle in the list. Once the new proximity data received, the vehicle will reach in the Selection State (SE). As shown in **Figure 10**, a vehicle in the selection state first tries to connect to the existing cluster to minimize the number of clusters. Hence, the source vehicle (SV) first checks the total number of vehicles, their position conjointly, and the state of each vehicle in its NVT.

If the vehicle finds a cluster head in its NVT, and the number of members in the cluster is lower than the maximum number of members allowed, the SV will attempt to connect to the existing CH. In the NVT, if none of the neighboring vehicles are listed as CH or the vehicle is unable to connect to any of the neighboring CHs, the vehicle inspects the neighboring vehicles in the semi-cluster head (SCH) state. If there are vehicles in the SCH state in its NVL, the source vehicle tries to connect the existing semi-cluster head. If none of the neighbor vehicles are listed as CH or SCH, the SV checks the neighboring vehicle in Selection State. If the SV discovers the vehicles in SE in NVT and it has the lowest average speed and the maximum distance from its current location to the zone boundary (i.e., longest lifetime) among them, then it will take the role of CH. Otherwise, the SV becomes

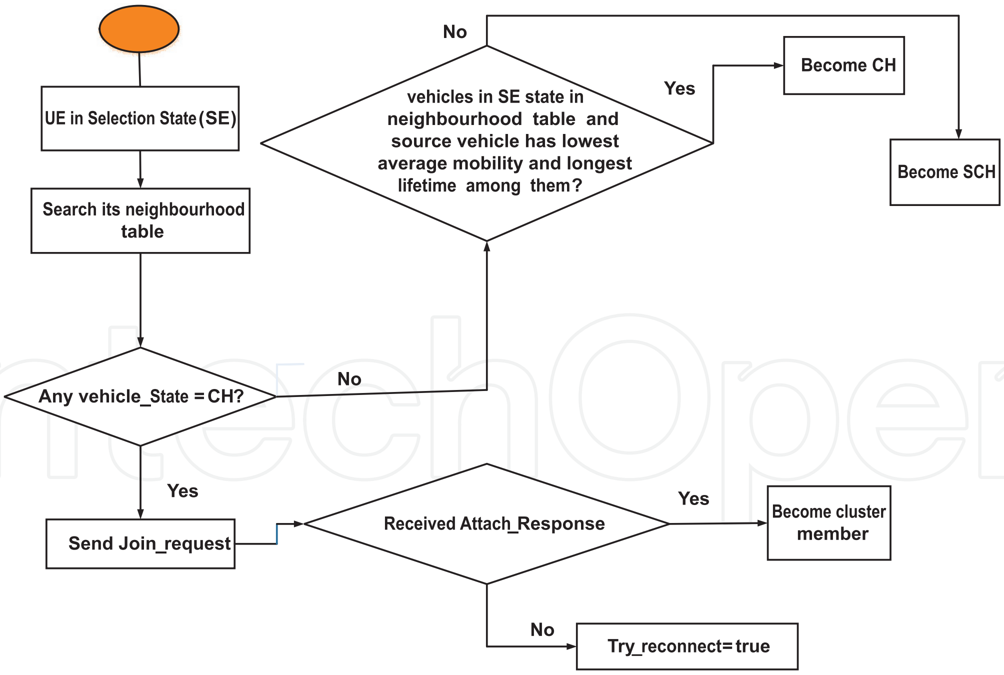

Figure 10.
CBC-V2V clustering approach.

an SCH. SCH is the state the vehicle has no potential neighboring vehicle that can connect to it.

4.4 Cluster head and semi-cluster head selection

Upon receiving the new proximity data in a neighboring table, an SV search the NVT during the time period T_{search} to check the vehicles in CH, SCH, and SE state. If none of the neighbor vehicles are recorded either as CH or SCH, the vehicle will check the neighboring vehicles in the SE states. If there are the vehicles in SE state in the NVT and the SV has the most reduced average speed and a maximum distance from its current location to the zone boundary (i.e., longest lifetime), at that point it becomes the CH. The algorithm for the CH and the SCH selection is presented in Algorithm 1. Each vehicle calculates its average speed periodically. If none of the neighbor vehicles are recorded either as CH, SCH, or SE, a source vehicle will take the role of SCH. In case the vehicle in the SCH state gets any joining request from a neighboring vehicle during the time period T_{SCH}, then it will take the role of the CH. Otherwise, it will reach in the SE state and require a re-registration to receive new proximity data.

Algorithm 1. CH and SCH selection

```
while $T_{search} \neq 0$ && there is no potential neighbouring to connect ($V_{State} \neq CHorSCH$) do
    if $V_{State} = ALL_{SE}$ then
      The SV will compare its $S_{SV}$ and $T_{Life}$ with other vehicles in NVL;
    if $S_{SV} < S_{ALL}$ and $T_{Life} > T_{ALL}$ then
      $SV \rightarrow CH$;
      else
       $SV \rightarrow SCH$;
      end if
    end if
```

```
    if $T_{SCH} \neq 0$ then
        $SCH_i$ receive any joining request from neighbouring vehicle;
        $SCH \rightarrow CH$;
    else
        $SCH \rightarrow SE$;
    end if
end while
```

4.5 V2X sidelink channel structure

Using communication mode 3, we suggest the 3GPP standard-based V2V sidelink channel structure as shown in **Figure 11**. The figure shows that an eNB reserves 10 D2D subframes on uplink cellular traffic channels in the time division multiplex (TDM) manner. The D2D subframe repetition rate is 100 ms. Each subframe contains two slots; hence a single carrier offers 20 slots for sidelink communications. The RBs are used to transmit data and control information. The data is transmitted using transport blocks (TBs) over the Physical Sidelink Shared Channels. Sidelink control information messages are transmitted over the Physical Sidelink Control Channels (PSCCH) [16]. The number of RBs in a slot depends on the bandwidth of an LTE-V network cell. Using a 3 MHz transmission bandwidth, there will be 15 RBs in 1 slot available for the D2D communication.

4.6 CBC-V2V communication

Our proposed CBC-V2V communication for safety message transmission is shown in **Figure 12**. As seen, the intra-cluster communication procedure between cluster members V_{A1} and V_{A2} belongs to a cluster CH_{A0} and inter-cluster communication from V_{A1} to the vehicle V_{B1} which belongs to a neighbor cluster CH_{B0}. For the rest of the vehicles in the network the same procedure will follow. A CH acts as a ProSe gateway node for vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (I2V) communication. The CH utilizes the Physical Uplink Shared Channel (PUSCH) uplink grant allocated during the random access procedure to send the RRC connection request along with the data structure called cluster_info. In the cluster_info, each CH keeps the information such as the CH_{ID} and the number of CMs attached to it. Based on the cluster_info in the RRC connection request, an eNB dynamically allocates resources to a CH for D2D communication. At the cluster level, each cluster head further schedules the resources among its CMs using the new cluster-based round-robin scheduling as described below.

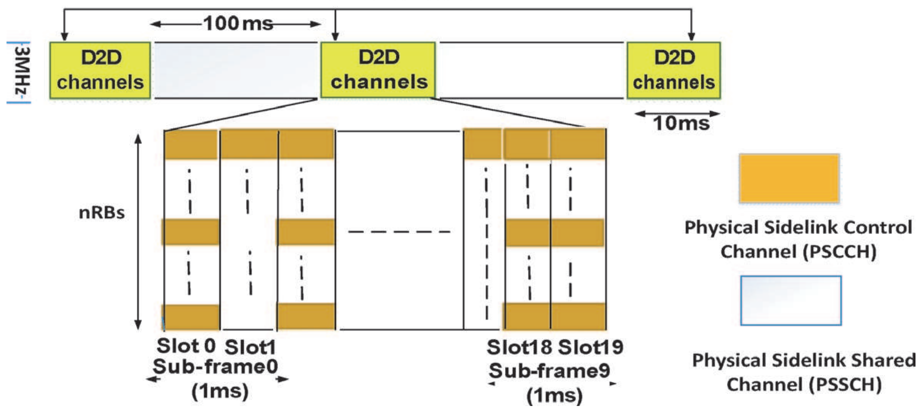

Figure 11.
V2V sidelink subframe structure.

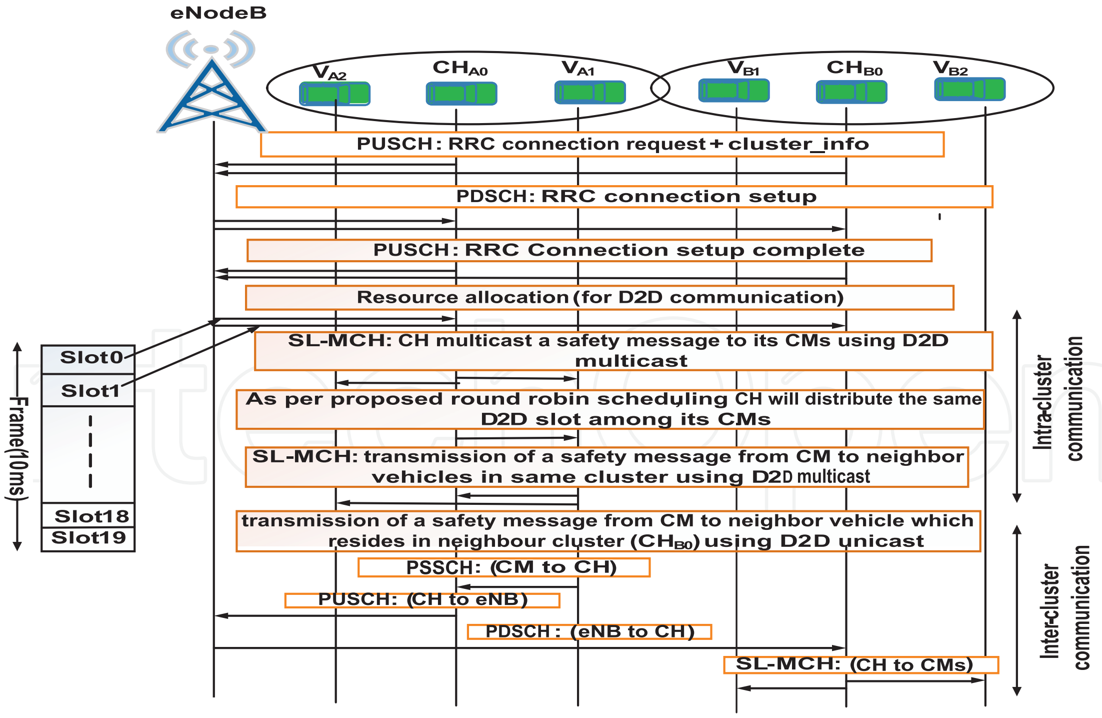

Figure 12.
CBC-V2V communication over sidelink channels.

Radio resources are initially allocated to the CH for each cluster of nodes. The CH then conducts round-robin resource scheduling among its CMs (i.e., vehicles) based on the vehicle ID. The round-robin scheduling approach is based on the idea of being fair to all active users in the long term by granting an equal number of physical resource blocks (PRBs). Our proposed resource allocation scheme is operated by dynamically assigning the same slot to the multiple users, in turn, using node IDs in ascending order. Subsequently, members of a cluster can share the same slot in turn to transmit their own CAM.

As shown in **Figure 11**, 10 subframes for D2D communication show up in every 100 ms which are shared between different clusters. Since each cluster is designated one slot, the same subframe will support two clusters. In the example, slot 1 is assigned to CH_{A0} and slot 2 is assigned to CH_{B0}. When the resource is allocated, the CH chooses PRBs within the available slot to transmit its posses CAM to its CMs in the multicast mode. A ProSe-enabled node cannot receive and decode the D2D message while it is transmitting, due to the half-duplex nature of most transceiver designs. Therefore, in the cluster, when one vehicle is transmitting, the rest of the vehicles will receive the CAM from the transmitting vehicle. Each safety message can be accommodated utilizing four PRBs based on the selected modulation and coding scheme and the packet size. On completion of the transmission from the CH, it will assign the same slot to its CMs. The next vehicle V_{A1} is thereby allocated the same slot on its turn based on its vehicle ID. Then V_{A1} multicast its own safety message to its neighboring vehicles. The same procedure will follow by the remaining vehicles in the cluster. To maximize reuse of the spectrum, the same D2D resource can be assigned to different nonoverlapping clusters.

In this architecture, the inter-cluster communication is required to share safety messages by vehicles which are found at the edge of the two neighboring clusters. In the example, vehicle V_{B1} is in the neighbor list of V_{A1} but out of range of its CH_{A0}. Therefore, direct communication is not conceivable between V_{A1} and V_{B1}. In this case, CH_{A0} collects the safety message from its cluster member V_{A1} over the D2D Physical Sidelink Shared Channel and transmits to the eNodeB over the LTE interface in the unicast mode. At that point, the eNodeB conveys the safety traffic message to a concerned neighbor CH_{B0} over the LTE interface. The CH_{B0} multicasts the safety message to its cluster members V_{B1} and V_{B2} via the LTE-D2D PC5 interface.

5. Simulation model

An OMNET++ version 5.1.1-based simulation model is developed utilizing the SimuLTE library [32] that utilizes the INET framework 3.4.0. For enhanced traffic simulation, GPS data incorporation, and mobility support, we utilized the Veins Package with a realistic mobility model generated by the microscopic road traffic simulation package: Simulation of Urban Mobility (SUMO) [33]. To add the mobility support feature in SimuLTE, a new interface known as vehicularMobility module has been added. This new mobility model can be implemented by the TraCIMobility module defined by the Veins. There is another mobility module known as INETMobility present in the INET framework. A vehicle can utilize only one mobility module during the simulation; therefore both modules (i.e., INETMobility and vehicularMobility) are defined as a conditional module within the Ned file. Veins use the OMNeT++ API to create and initialize the new module dynamically. When a new vehicle is created, it needs to obtain an IP address to communicate. SimuLTE demands the assignment of IP addresses to the IPv4NetworkConfigurator module provided by INET.

A new parameter, i.e., d2dcapable, is utilized in the .ini file to enable direct communication between two UEs. Most of the PC-5 operations at each layer of the LTE stack are created by extending pre-existing SimuLTE capacities. For each D2D competent user, an LTE binder keeps up a data structure that contains the set of directly reachable destinations. In expansion to the existing DL/UL ones in SimuLTE, a new flow path, PC-5, has been distinguished. From the UE point of view, IP datagrams reach the PDCP layer and either the PC-5 or the UL directions can be associated with the corresponding flow, depending on whether the destination is in the LTE Binder peering table or not. The detailed description of configuring D2D communication in OMNET++ with SimuLTE is given in [34]. The key simulation parameters are summarized in **Table 4**.

We modified the existing D2D communication model in the SimuLTE to support our proposed cluster-based cellular V2V architecture. **Figure 13** shows the CBC-V2V communication model consists of an access network entity (single eNodeB) and core network entities (MME, HSS, and GMLS) are utilized to support our proposed EPC Level Sidelink Peer Discovery model. In the simulation, we design a multilane highway scenario where the vehicles are distributed according to the Poisson process. The vehicles form the clusters using our proposed clustering scheme for D2D communication. To implement our proposed clustering scheme, we utilize the sample source code accessible online [35]. Each cluster node keeps up neighborhood table that contains its neighbor’s ID and their state. In the simulation, we include scenarios of both multicast and unicast shown in **Figure 12**. The model is simulated for both scenarios utilizing the parameters presented in **Table 4** for 800 seconds. At the MAC layer in the SimuLTE, we modified the scheduling model (i.e., LTEDrr) to implement our proposed round-robin scheduling scheme presented in Section 4. Utilizing the proposed round-robin scheduling technique, each cluster node receives an equal share of the radio resource for D2D communication.

5.1 Performance analysis

Using the number of clusters/km and the traffic load (i.e., number of vehicles/cluster) parameters, we examine the overall end-to-end delay, resource utilization,

Parameter	Value
Maximum velocity	40–70 km/h
Number of vehicles	96 vehicles/km
Road length and number of lanes	5 km and 4 (i.e., 2 in each direction)
Carrier frequency	2.6 GHz
Duplexing mode	TDD
CAM generation rate	10 packets/sec
Transmission bandwidth	3 MHz (i.e., 15 RBs)
Path loss model	Highway scenario
Fading model	Shadowing
eNodeB Tx power	46 dBm
UE Tx Power	26 dBm (Uplink), 5 dBm (Sidelink)
Coverage range	1000 m
Noise figure	5 dB
Cable loss	2 dB
Simulation time	800 s
Packet size	340 bytes
T_{safety}	100 ms
Number of vehicle/cluster	12
$CH_{\text{maxmember}}$	11

Table 4.
Main simulation parameters.

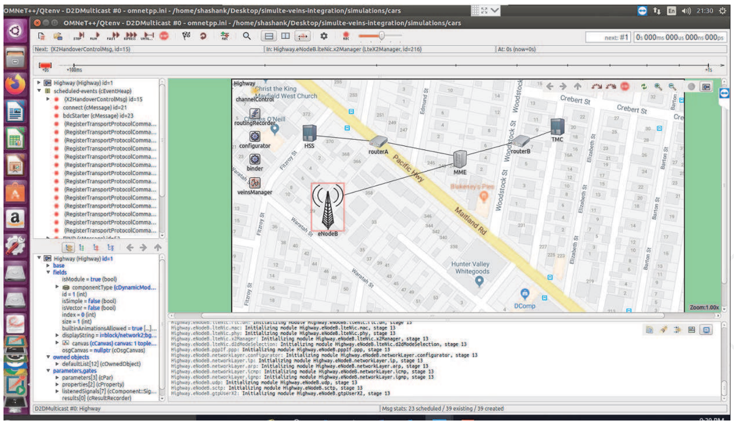

Figure 13.
CBC-V2V simulation model.

signaling overhead, and data packet delivery ratio performance of our cluster-based D2D vehicular network architecture. The following performance metrics are used to evaluate the proposed algorithm.

5.1.1 Control signaling overhead

The signaling overhead is measured for the proposed EPC level peer discovery and the D2D packet communication techniques. The overall signaling overhead of the network can be calculated as

$$X_{SO}(c) = \sum_{i \in N} \left(\overline{x}_{pd} + \overline{x}_{d2d} \right) \tag{1}$$

where $\overline{x}_{pd}$ represents the average signaling overhead in bits related to the control signaling required for the peer discovery and $\overline{x}_{d2d}$ represents the average signaling overhead related to the control signaling required for the D2D communication. $\overline{x}_{pd}$ can be calculated as the number of slots used for peer discovery out of the total number of n subframe available in the cell i as

$$\overline{x}_{pd} = \frac{x_{ir1} + x_{ir2} + x_{ir3}, \ldots, x_{irn}}{n} \times 100 \tag{2}$$

Similarly, we calculate $\overline{x}_{d2d}$ the overhead for the D2D communication and calculate the overall signaling overhead. **Figure 14** shows the signaling overhead required by the CBC-V2V, the default 3GPP ProSe algorithm, and the LTE-Advanced algorithm using conventional cellular architecture. The results clearly show that the CBC-V2V introduces lower signaling overhead compared to the other two standards which can be used in a VANET. The main reason for the performance improvement is the lower control signaling requirement for the CBC-V2V algorithm. The major benefit comes from our ESPD algorithm which requires less control message exchange for peer discovery compared to existing peer discovery models described in Section 4. Unlike the existing 3GPP peer discovery model, in the ESPD algorithm, a vehicle receives the proximity information after the successful registration which requires very less control message exchange as shown in **Figure 2**. The smaller control signaling overhead requirement will improve the performance of safety services and guarantee the timely delivery of active safety messages.

Figure 15 shows the overall resource utilization of the CBC-V2V algorithm for safety services. We compare the results with the standard ProSe solutions in terms of a number of occupied RBs. The efficient scheduler minimizes resource utilization and distribution levels. In the CBC-V2V, each of the CH acts as a scheduler and distributes the resources among its CMs using our proposed round-robin scheduling. Two clusters can be served in a single subframe, and nonoverlapping clusters can share the same resource. Resource utilisation of the CBC-V2V algorithm is lower compared to 3GPP ProSe algorithm due to lower control signal requirements, cluster architecture and efficient resource allocation technique of the algorithm.

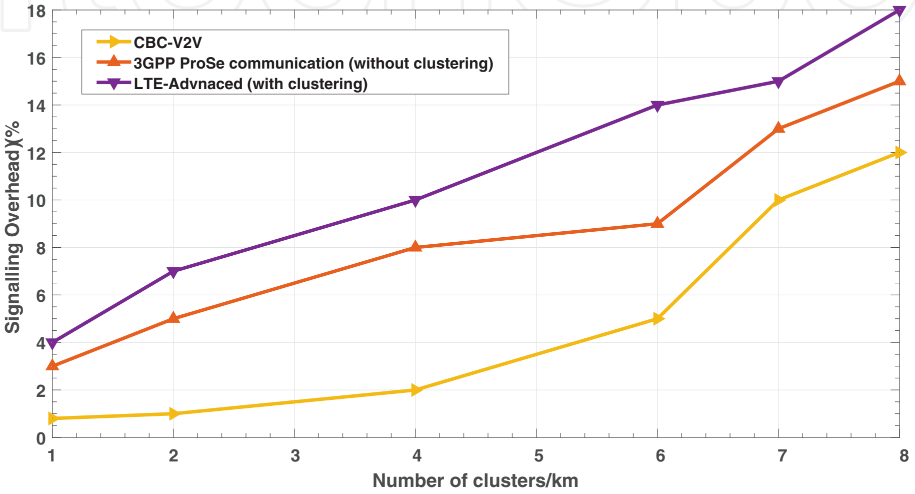

Figure 14.
Performance comparison in terms of signaling overhead.

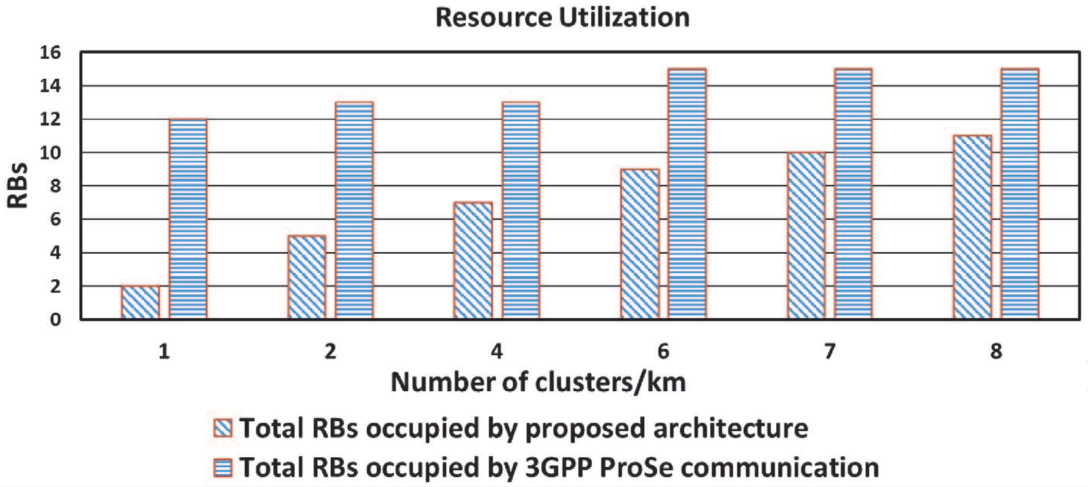

Figure 15.
Performance comparison in terms of total occupied RBs.

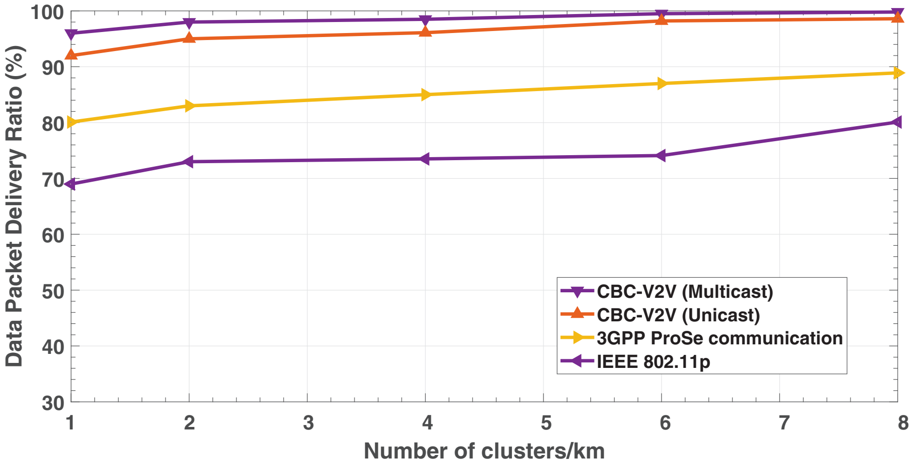

Figure 16.
Performance comparison in terms of data packet delivery ratio.

Figure 16 shows DPDR of the CBC-V2V and compares it with two existing standard procedures. The DPDR is characterized as the proportion of the total number of received safety packets to the total number of scheduled safety packets. Due to the closer vicinity of vehicles, the DPDR value increases with the number of clusters. The system based on IEEE 802.11p shows the lowest DPDR value because packets are lost due to collisions then the proposed D2D packet communication technique which is contention-free. Subsequently, the packet loss probability is low, due to transmission channel condition.

5.1.2 Total end-to-end delay

The total end-to-end delay (δ_{E2E}) for a transmission of a safety message consists of two major delay components as

$$\delta_{E2E} = \delta_{PD} + \delta_{D2D} \tag{3}$$

where δ_{PD} represents the total delay in peer discovery, which is the time difference between sending a request for registration and receiving an eNodeB response and δ_{D2D} represents the total delay in D2D packet communication, which is the sum of the intra- and inter-cluster delays in communication. To ensure timely delivery of active safety messages, the total end-to-end delay (i.e., δ_{E2E}) of the safety message should be less than the required delivery delay (i.e., $Tsafety$).

Figures 17 and **18** present the delay analysis of the CBC-V2V algorithm as a function of the total number of clusters formed based on the number of vehicles/km. **Figure 17** evaluates and compares the peer discovery delay of the ESPD with the 3GPP ProSe peer discovery model described in Section 4. In the proposed ESPD, the peer discovery delay is the time taken by each vehicle for successful registration. In the registration response, each vehicle receives its current traffic profile which contains the list directly reachable vehicle in its vicinity. Due to the less resource utilization and minimal control signaling overhead requirement, ESPD shows the lower delay values for the peer discovery task compared to the existing 3GPP ProSe peer discovery model. **Figure 18** shows the overall end-to-end packet delay of the CBC-V2V. The results show that the CBC-V2V outperforms the traditional approaches such as IEEE 802.11p, LTE-D2D, and LTE for the safety message transmission in a VANET.

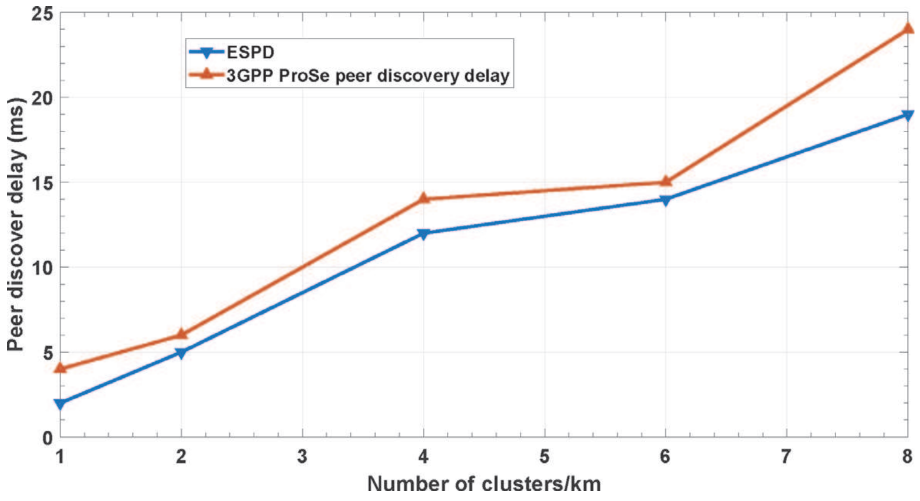

Figure 17.
Performance comparison in terms of peer discovery delay.

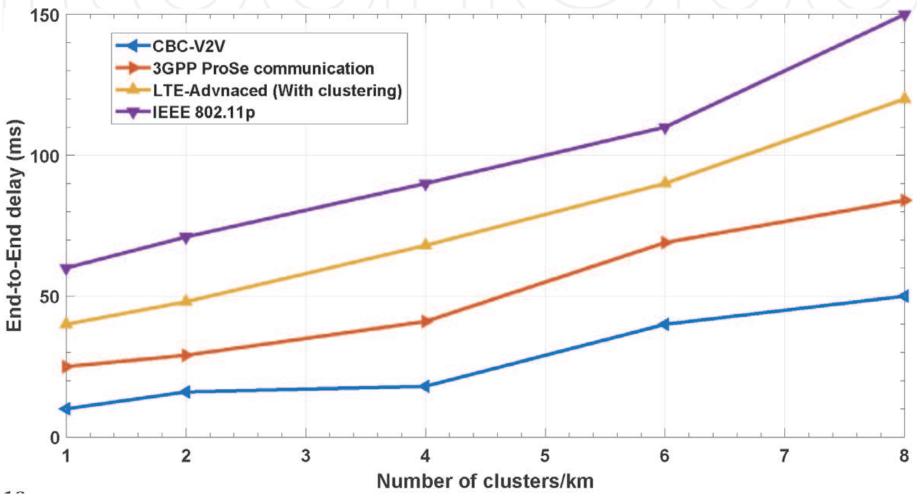

Figure 18.
Performance comparison in terms of E2E packet delay.

6. Conclusion

This chapter has introduced an advanced new cluster-based V2V packet communication architecture combined with an EPC level peer discovery model suitable for vehicular safety applications. The ESPD model reduces the control signaling overhead and end-to-end delay with the awareness of proximity utilizing the GPS information. The CBC-V2V also combines a cluster-based round-robin scheduling technique to distribute the radio resource among the cluster nodes. The CBC-V2V can improve resource utilization and reduce the end-to-end delay to meet the QoS requirements of the safety services in VANETs. Simulation results show that the CBC-V2V offers higher QoS than do the IEEE 802.11p and other LTE networking architectures. The research will be further extended to examine the vehicular network performance in different road terrains and transmission conditions.

Abbreviations

VANET	vehicular ad hoc network
ITS	intelligent transportation system
V2V	vehicle-to-vehicle
V2N	vehicle-to-network
V2P	vehicle-to-pedestrian
V2I	vehicle-to-infrastructure
V2X	vehicle-to-everything
RV	remote vehicle
HV	host vehicle
RSU	road side unit
DENM	decentralized environmental notification messages
STCH	SL traffic channel
SBBCH	SL Broadcast Control Channel
SCI	SL control information
PSSH	physical SL shared channel
PSDCH	physical sidelink discovery channel
ProSe	proximity service
DPDR	data packet delivery ratio
CSMA/CA	carrier-sense multiple access with collision avoidance
SPS	semi-persistent scheduling
LTE	long term evolution
eNB	eNodeB
UE	user equipment
E-UTRAN	Enhanced UMTS Terrestrial Radio Access Network
EPC	evolved packet core
CAM	cooperative awareness message
CBC-V2V	cluster-based cellular vehicle-to-vehicle
ESPD	evolved packet core level sidelink peer discovery
CACC	cooperative adaptive cruise control
SC-FDMA	single-carrier frequency division multiple access
GNSS	global navigation satellite system
EPUID	EPC ProSe subscriber ID
ALUID	application layer user ID
PSS	primary synchronization signal
SSS	secondary synchronization signal

MIB	master information block
SIB2	system information block 2
MRD	maximum reuse distance
FCD	floating car data
CMs	cluster members
CH	cluster head
ICI	inter-carrier interference
TTI	transmission time interval

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