POLITECNICO DI TORINO

Master's Degree in Communication and Computer Networks Engineering

Master's Thesis

Semi-persistent data scheduling analysis over ultra low latency communication networks

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Abstract

In this thesis we analyse performances of communication in a railway environment, where requirements are very strict in terms of latency and reliability. Nowadays on the train backbone, time sensitive networks are used because they meet those strict requirements.

The scope of this thesis is to analyse performances of different algorithms to see if it is possible with current technologies to provide a wireless connection above the time sensitive network, working on the so called wireless train backbone, and practically implement a wireless link in a wired network. The first scheduling algorithm that are analysed is the semi-persistent scheduling, the algorithm currently standardized by 3GPP for cellular communications without the eNodeB coordination. The algorithm is tested using NS3, a network simulator. The second algorithm that is tested is the self-organized time division multiple access algorithm. This algorithm has been tested in vehicular environment and under certain condition has shown better performances then semi-persistent scheduling algorithm. In this thesis it is tested using a MATLAB implementation and applied on the same scenario of semi-persistent scheduler.

Dans cette thèse, nous analysons les performances de communication dans un environnement ferroviaire, où les exigences sont très strictes en termes de latence et de fiabilité. De nos jours sur la dorsale du train, des réseaux sensibles au temps sont utilisés car ils répondent à ces exigences strictes.

Le but de cette thèse est d'analyser les performances de différents algorithmes pour voir s'il est possible avec les technologies actuelles de fournir une connexion sans fil au-dessus du réseau sensible au temps, en travaillant sur ce que l'on appelle la dorsale du train sans fil, et de mettre en œuvre pratiquement une liaison sans fil dans un réseau câblé. réseau. Le premier algorithme d'ordonnancement analysé est l'ordonnancement semi-persistant, l'algorithme actuellement standardisé par 3GPP pour les communications cellulaires sans la coordination eNodeB. L'algorithme est testé à l'aide de NS3, un simulateur de réseau. Le deuxième algorithme testé est l'algorithme d'accès multiple à répartition dans le temps auto-organisé. Cet algorithme a été testé en environnement véhiculaire et dans certaines conditions a montré de meilleures performances que l'algorithme de programmation semi-persistant. Dans cette thèse, il est testé à l'aide d'une implémentation MATLAB et appliqué sur le même scénario de planificateur semi-persistant.

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would say thank you to my family for love I receive from them, the courage I needed and because they spurred me to be more determined.

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Chapter 1

Introduction

Vehicular communications are getting more and more important in communication field, because it is thought that autonomous driving would provide better safety, as stated in [1], and efficiency, in respect with human driven mobility, more prone to errors. In [2] they estimate that autonomous driving would decrease traffic, it would reduce carbon oxide emission, increasing mobility. Car-to-car and car-to-infrastructure communication are just few examples of communications needed for this technological transition, but the evolution of mobility is not just related to car driving.

Inspired by car environment, the same idea could be extended in the railway environment, thinking in the future about autonomous-driven trains. Nowadays the trains are spaced in the system in inefficient way, because the space among one train and the following one must be very high for safety reason, exploiting poorly the infrastructure capacity. Moreover, the train structure itself is rigid and this rigidity implies many disadvantages in terms of maintenance and traffic engineering. Using the same idea of car environment, the consists in a train can be seen as independent and a track can evolve ongoing by single consists that can join or leave the group, according to their destination. A similar concept is used in car mobility by platooning, where cars, or trucks, could create groups of vehicle rolling compact, in order to save space and reduce air friction. In order to establish this kind of groups of vehicle, all the members must be in communication. This kind of communications are challenging in terms of reliability and latency.

In the trail-way environment, the requirements are strict because high speed is involved, and high density can be a possible scenario trains mast be able to manage. The industrial requirements for latency must stay below 1 ms and for reliability of 1 packet lost every 10^6, and they are similar to railway communication in order to deal with high speed and low distance among consists. This kind of requirements are met in industrial environment by time sensitive networks (TSN). This kind of wired networks have all synchronized nodes and evident latency restriction per node in the network, as well as high reliability and limited jitter.

Currently all the consists in a train are physically linked and so wired. ON one hand this connection is effective for low interference and implementation of TSN, but, on the other hand, this network is static. Physically separation among consists in the train means exploit a wireless channel among consists for control and management communication, forming the so called Wireless train backbone communication (WLTB), as stated in one of objectives in [3]. Exploiting a wireless configuration, the advantage resides in the flexibility and scalability of the communication inside the train. Moreover, the train topology can be variable so that space efficiency can improve.

So the main scope of the project is to find a way to introduce wireless links inside a local area network that satisfies time sensitive networks standard and continue to satisfy the standard independently from wireless or wire links: wireless links should not impact on the time sensitiveness of the network.

For wireless communication there are different possibilities. First of all a wifi approach was discussed, in particular the newest IEEE 802.11 BD, for the technology capability to naturally handle local area networks. As major alternative, 5G approach was considered for the capabilities of this technology. These two technologies are deeply explained and analysed in [4]. It is important to mention that from long time there is a comparison among cellular technology and wifi technology, discussing which one is better for vehicle communication. Thinking at the data rate constrains, visible light communication was considered. This technology, described in [5], is already proposed for vehicle platooning as analysed in [6]. Lastly, concerning the cellular communication, the 4G approach was considered because of some advantages such as already existing protocols and prototypes. In particular the C-V2X already standardized by 3GPP offer two possibilities: LTE D2D, standardized in releases 12 and 13, and LTE V2X, standardized in releases 14 and 15.

Safe4RAIL analysed all the proposals already described and finally decided to choose the LTE V2X approach for market availability, because a ready prototype was important to speed up the process of real implementation. Among the issues this kind of approach has, the main question is how good the standardized scheduler, the so called semi-persistent scheduler, or in other words, the main question is if the standardized scheduler can satisfy latency requirements and how reliable it is.

In chapter 2 we would study some literature about resource allocation and scheduling, vehicular networks and proximity service. In particular we would explain the static and dynamic allocation, the exploitation of vehicle computing capabilities for a cloud-based scheduling and finding optimal solutions using game theory

A study would be performed in section 3.3 to determinate if this algorithm is strong enough. For this purpose, we will study the algorithm response in function of packet size, inter-distance among vehicles, variable packet size and a study about reliability. An alternative on this algorithm is present in Optical Orthogonal Codes (OOC), a scheduler that is considered a valid alternative to Dedicated Short range communication DSRC standard. This second scheduler would be simulated in MATLAB algorithm in section 3.3 and would be compared with the results obtain by NS3 simulation of semi-persistent scheduler.

Finally in chapter 4 we report our comments and conclusions and we explain all the future works can be developed starting from this thesis.

Chapter 2

State of the art

In this chapter we illustrate the most recent studies about resource allocation, scheduling in vehicular environment in general.

We then analyse more deeply the structure of semi-persistent scheduling and self-organizing time division multple access, in order to have a clearer idea about how they work and how they would be used in the simulations performed in section 3.3.

2.1 TSN: application for ultra reliable and low latency communications

Latency, as it is defined in [7], is the time elapsing from the instant of the beginning of transmission by the transmitter to the complete reception by receiver. The term ultra-low-latency (ULL) refers to latencies in the order of few milliseconds or less then one millisecond.

ULL applications often require the so called deterministic latency or in other words, the latency must not exceed a certain bound, an example of application of this kind is industrial automation. Some others may require the so called probabilistic latency, i.e. a pre-determined delay bound that are met with a pre-defined probability; an example of these applications is a multimedia streaming. In order to guarantee these strict requirements the time sensitive networks are used.

TSN is standardized by IEEE 802.1 working group. Its aim is to develop standards in areas like LAN/MAN architectures, inter-networking among IEEE 802 LANs and MANs, security, IEEE 802 network management, protocol layers higher than MAC and LLC layer. Their work is continuously revised: the current standard is IEEE 802.1Q-2018. The standard specifies the bridge as a network entity within 802.1 enable communication among TSN network and an external network like a IEEE 802 LAN. It is important to notice that TSN can be deployed over Ethernet, to support real-time industrial automation and control system applications. In case instead the physical layer used in the bridge is wireless, then some PKI are normally used, depending on applications.

[8] illustrates that the initial standardization had started with IEEE 802.1 Audio and Video Bridging, but then the task group evolved into time sensitive networking task group in 2012 because other user cases like industrial and automotive application were taking into account.

The most useful standards for the scope of this thesis are the IEEE 802.1AS-2011 and IEEE 802.1Q-2018. The former standard describes timing and synchronization for time-sensitive application in bridged local area networks, while the latter standard deals in general with bridges and bridged networks. In particular inside IEEE 802.1Q-2018 the amendment IEEE 802.1Qbv describes the scheduled traffic.

The standard specifies the flow concept, characterized by quality of service requirements like latency or bandwidth requirements. The definition of TSN flow as stated in [7] is "an end-to-end unicast or multicast network connection from one end station (talker, sender) to another station(s) (listener(s), receiver(s)) thought the time-sensitive capable network"; the term *flow* is sometimes referred as *stream*. Each TSN flow is defined by a priority code and by VLAN ID. In order to guarantee requested resources, the network has admission control and stream reservation procedures. These procedures are performed in a centralized or distributed manner, depending on the complexity of the network, using the recommended YANG model and NETCONF protocol to configure network devices. Lastly, Path control element protocol uses existing routing algorithm for traffic-engineered networks.

Is important that each node is synchronized with the others, so that the network became time-aware and can compute peer path delay and residence time inside each node: these information are fundamental for the scheduler and for routing choices. All the nodes'clock synchronization process is based on master-slave hierarchy and it is described in the standard IEEE 802.1AS-REV.

The concept of delay in TSN networks, do not care about average delay nor fastest delivery, but the most important parameter is the *worst case delay*. In order to reduce the delay as small as possible each node has some traffic shaping policies. Moreover, to deal better with scheduled traffic slots, during which some packets of certain TSN flow are forwarded by a node, a guard band is introduced, whose size is the largest possible interfering fragment. In this way the node can use preemption and manage more effectively the traffic.

Due to very high reliability requirements, some mechanisms of packets replication is used. They are replicated taking care of address, traffic class and path information. Nodes must have duplicate frame elimination capability, in order to recognise packet replica and eventually drop them. The management of packet replication is not trivial and to implement this function a centralized management is required.

2.2 Wireless TSN

In Release 16, 3GPP has considered the possibility to integrate time sensitive networking networks into 5G systems. As stated in [9], 3GPP has supported TSN configuration models, internetworking with TSN, simplified traffic scheduling, time syncronization features and time sensitive communication traffic classes. Practically, in release 16, a 5G network node can be seen as a logical TSN bridge and the entire network as a TSN network.

In [9] is mention anywhere the possibility of a wireless 5G connection that satisfies TSN requirements. Wireless links are more prone to errors and delays, due to interference; also security could be an issue.

In the following we would illustrates some studies to have a wireless link that satisfies TSN characteristics. In order to do so, the most important feature to define are requirements. For different applications, we have different requirements to satisfy. For example, in [10] the machine type communication has constrains on reliability at 99.999% and on latency set to 1 ms. For [11], in industrial environment (motion-control), the maximum end to end latency cannot exceed 0.1 ms and the reliability must be 99.9999%. As [12], Intelligent transportation system must satisfy the same requirements of URLLC so again e2e latency of 1 ms and reliability of 99.999%. For what concern the Safe4RAIL requirements, listed in [] the maximum allowed end-to-end latency must be lower than cycle time of 40 ms and a reliability of 99,999%, or in other words, a probability of error equal to 0,001 percent, it means one error every hundred thousand transmissions.

In order to define the key challenges towards wireless TSN networks, the Avnu Alliance wrote a white paper published in January 2018. The Avnu Alliance is a consortium consisting of professional, automotive, consumer electronics and industrial manufacturing companies, working on defining a common certification for iter-operable TSN standards. In the white paper written by Steven F. Bush et al. [13], they state five points to meet in order to deploy wireless TSN: wireless configuration of wired TSN, hybrid wired-wireless time synchronization, wireless TSN scheduling, wireless redundancy for wired TSN and wireless TSN switch deployment.

The paper states that wireless configuration and switch deployment are relatively easy, the other phases have some gaps: tightness of synchronization, the possibility of a wireless scheduler to be compliant with IEEE 802.2Qv, that would be configurable and take care of synchronization errors, the integrability of wireless interface into IEEE 802.1CB seamlessly.

Furthermore, the paper raises an issues related to cybersecurity. Indeed, authentication and availability are the most important functions into an industrial system. In order to get them, the paper suggests the use of private key exchange and for transmitting he keys, they encourage to take care of the development of quantum key distribution and they suggest the use of IEEE P1913 keychain YANG model to manage key lifetimes.

Finally, [13] concludes arguing that the most challenging issue is reliability with determinism, because even if latency requirements can be met and retransmission can be considered to improve reliability, the target message must reach its destination before the end of the scheduled period, to satisfy deterministic property.

The paper written by A. Mildner et al. in May 2019 [14] first considers the four key pillars: time synchronization, bounded low latency, ultra reliability and resource management. Considering as wireless medium a IEEE 802.11 physical layer, the authors have focused on the IEEE 1588v2 Precision Time Protocol (PTP), and 802.11 Beacon Frames and the internal Time Synchronization Function (TSF) for synchronizing clocks. For what concern ultra reliability and low latency, they say that even if we could consider retransmission into the latency period, the concept of latency and determinism is still under research. Finally, the resource management is possible exploiting wireless channel and it is more flexible than wired network. The final conclusions of the paper states that the wireless deployment of time sensitive networking is still at early development stage, especially for what concern clock synchronization and resource scheduling to meet bounded latency.

We can conclude after having analysed the current state of the art regarding wireless deployment of time sensitive networking that the implementation is still at initial stage and many gaps must be filled. One of the most important issues still remain the use of a scheduler capable of guaranteeing a bounded latency. So in the following we explore some known scheduler and their performances.

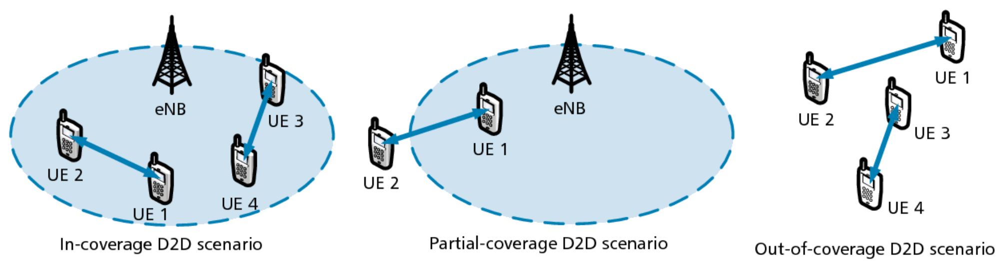
2.3 3GPP C-V2X roadmap

In order to implement the communication among consists we need to choose among different technologies. As reported in [15], Safe4RAIL has considered LTE, ZigBee, WirelessHART, Ultra Wide Band, Wi-Fi, ECHORING, Wireless Interface for Sensors Actuators, as well as futures technologies like SHARP, LTE Release 15 and 16 (5G), WirelessHP and Wifi 6 (IEEE 802.ax). Taking care of advantages and disadvantages from every technology the Safe4Rail2 consortium has chosen the LTE V2X technology as most appropriate for the scope of the project. In the following we would describe how C-V2X communication has evolved release after release, and how the 5G would modify it.

Since 3GPP release 12, a new interface was introduced: the so called PC5 over which the sidelink relies on. The sidelink is a new idea that add new functionality to the communication: users can communicate directly without necessarily rely on a base station. The sidelink is neither an uplink channel nand a downlink channel, but it is defined as a third independent channel. For its configuration, the sidelink is more similar to uplink than the downlink, because relies on the same single carrier frequency division multiple access (SC-FDMA) used in LTE uplink.

The main use of the sidelink is when the users are out of cell coverage: in this scenario they must communicate without the presence of a base station. This scenario implies a completely distributed management of resources. A second possible scenario is when just one user is in coverage but the other one is not covered by the base station. In this second scenario the first user can receive some information from the base station and handle the sidelink communication, reducing to the minimum the interference with the eventual users inside the cell. The second user would follow the first user choices because it would know the first one is under coverage. A third possible scenario is when both users are in coverage of a base band. In this configuration they can decide if communicate through the base station as in normal cellular communication, or they could exploit the sidelink to communicate device to device. The advantage of this scenario in respect with the first one is that the base station have all scheduling information of users inside the cell and can suggest a proper resource scheduling to D2D users, in order to reduce interference as much as possible. It must be noticed that uplink and downlink communication have higher priority than D2D communication, so in case the cell has reached the maximum capacity, the D2D communication cannot be a feasible choice.

Figure 2.1. Sidelink possible scenarios

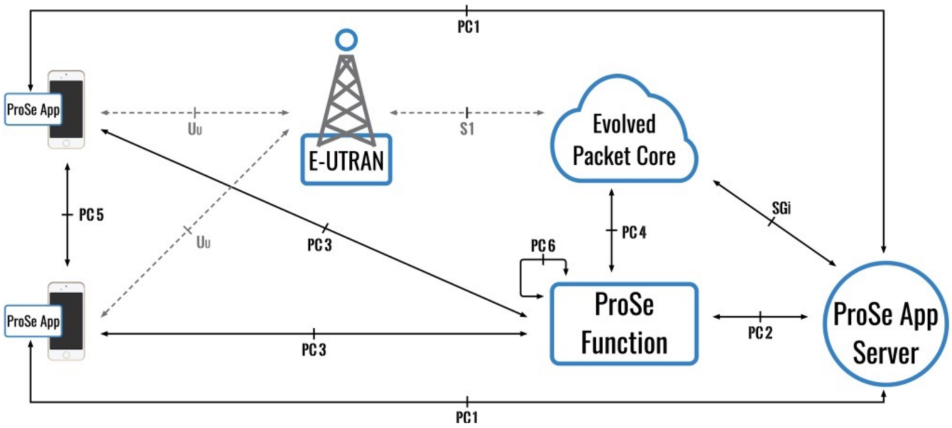


The sidelink can be different, depending on modes. From rel. 12 to rel. 15, up to 4 modes have been defined: mode 1 and mode 2 are defined in rel. 12, they are enhanced in rel. 13, mode 3 and mode 4 are defined in rel. 14. In rel. 15, 3GPP has enhanced the 4 modes with some extra services. Finally, in rel. 16, that will be frozen in March 2020, they will introduce an optional second interface with improved performances, known as NR V2X, consisting on 2 different modes and eventually 4 sub-modes for mode 2. Looking into the future development, release 17, scheduled for delivery in 2021, has the following objectives: NR Sidelink enhancement, NR Sidelink relay, Proximity based services in 5GS and enhancements of V2X services.

2.3.1 Release 12 and 13

Starting from Release 12 of LTE standard, 3GPP has formalized the Device-to-Device communications under the name of Proximity Services (ProSe). ProSe introduce an extension to the classic LTE reference architecture, defining new network elements, new functions and new set of interfaces as illustrated in Figure 2.2

Figure 2.2. ProSe reference architecture extension (from [16]), section 4.2



Alongside the classical interfaces Uu (which connects the UEs with the eNodeB), numerous new interfaces (PC1 to PC8 and SGi) enable direct communications between devices without requiring the data flow to pass through the network. The PC5 interface represents the air interface between UEs: it is denominated Sidelink, to distinguish it from the classic Uplink and Downlink that take place on the Uu interface.

Sidelink communications are based on the concept of resource pools, which determine the subsets of the UL resources that are dedicated to a specific UE-to-UE channel. Resource pools are formed by:

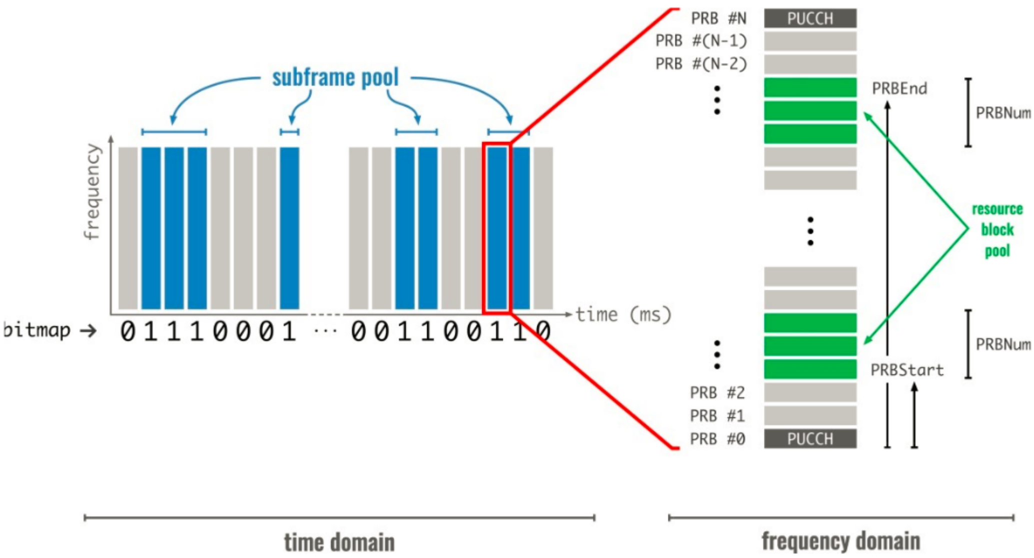
- subframe pool (in time domain), identifying a subset of the subframes
- resource block pool (in frequency domain), a subset of the PRBs

as illustrated in Figure 2.3.

In the time domain, the subframe pools are laid out according to a periodic structure. The channel occupation within the periods is determined by bitmaps (such as, for instance, the subframeBitmap-r12 in [17], section 6.3.8), whose '1' bits denote the subframes which are part of the resource pool, as illustrated in the time domain side of Figure 2.3.

Within each subframe marked with a '1', a resource block pool is defined in frequency domain by three parameters:

Figure 2.3. Structure of Sidelink resource pool



- PRBStart indicates the Physical Resource Block (PRB) starting from PRB #0, in correspondence to which the Sidelink starts;
- PRBEnd indicates the PRB, starting from PRB #0, in correspondence to which the Sidelink ends;
- PRBNum indicates the number of PRBs dedicated to the Sidelink above PRB-Start and below PRBEnd

A resource pool thus assumes the appearance of a pair of sub-bands within the uplink frequencies, as illustrated in the time domain side of Figure 2.3

There are two types of resource pools: TX resource pools and RX resource pools: receiving UEs shall have a RX pool associated to the TX pool of a transmitting UE.

At physical layer, separate resource pools are created in order to carry four new sidelink channels (defined in [18], section 5):

- PSBCH: Physical Sidelink Broadcast Channel,
  which carries system and synchronization information, transmitted by the UE;
- PSCCH: Physical Sidelink Control Channel,
  which carries control from a UE for ProSe direct communications;
- PSDCH: Physical Sidelink Discovery Channel,
  which carries ProSe direct discovery messages from the UE;

- PSSCH: Physical Sidelink Shared Channel,
  which carries data from a UE for ProSe Direct Communication.

ProSe supports both one-to-one and one-to-many communication paradigms, although the latter is reserved to public safety UEs, as expressed in [16]

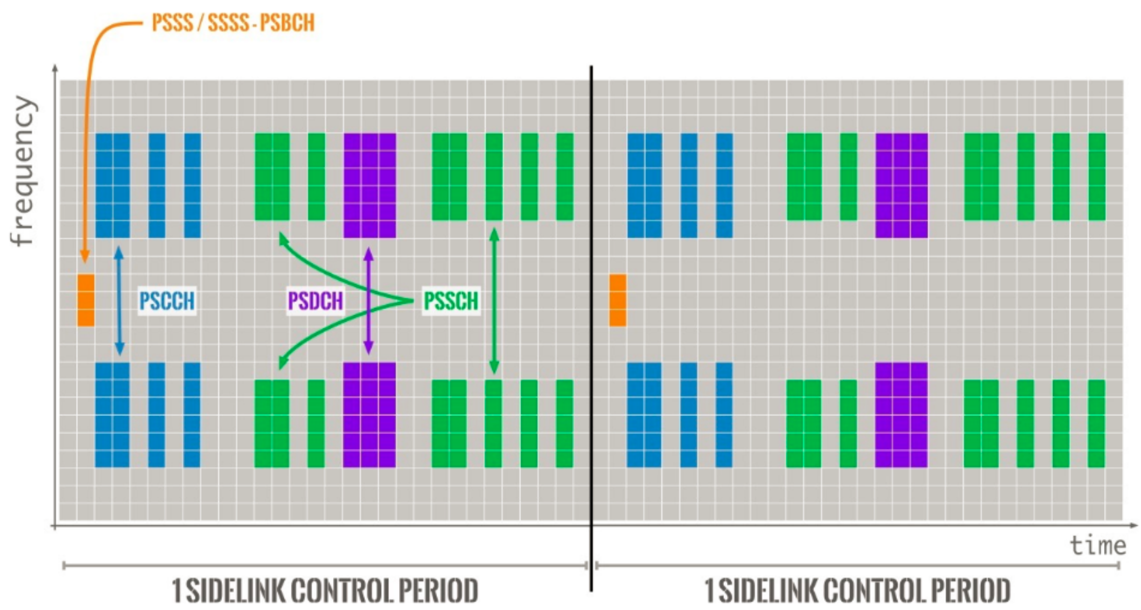
ProSe supports two communications modes, which differ on the allocation scheme adopted for transmission of the Sidelink Control Information (SCI) on the sidelink control channel (PSCCH):

- Mode 1: scheduled resource allocation
- Mode 2: autonomous resource selection

In mode 1, transmissions on the Sidelink are authorized by the installed network, which provides the transmitting UE with PSCCH resources to transmit the SCI in, and PSSCH resources to transmit data in. In mode 2, transmissions are unsupervised: transmitting UEs randomly choose the resources, within the PSCCH resource pool, in which to transmit the SCI.

The four sidelink physical channels are periodically interleaved in time, with periodicity equal to one Sidelink Control Period as illustrated in Figure 2.4, an example related to communication mode 2, wherein a PSSCH pool is statically allocated.

Figure 2.4. Example of sidelink time/frequency allocation



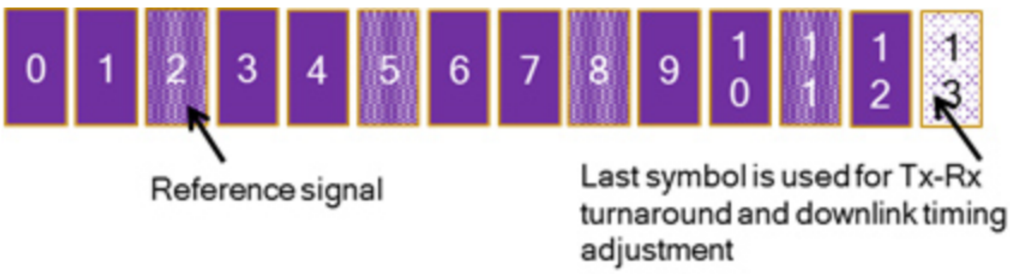
All the channels are implemented using OFDMA. The multiple access by different users is achieved by assign different sub-carrier frequencies. The available bandwidth is composed by resource blocks in frequency domain. Every resource block is composed by 12 sub-carriers each 15kHz wide. In time domain instead, a frame last for 10 ms, and it is divided into subframes, 1 ms long. Each subframe is further divided into two slots whose length is 0.5 ms. The resource block, in time, last for one slot in the time domain.

2.3.2 Release 14 and 15

In 3GPP release 14, short-range LTE V2X was defined, thus they introduced mode 3 and mode 4 in addition to the previous mode 1 and mode 2 from D2D communication. A new D2D interface is thus designed specifically for V2V communication, so specifically addressed for high speed nodes (maximum considered speed at 250 km/h [19]) and high density network (up to thousands of nodes).

To cope with high speed - and thus with Doppler effect - additional demodulation reference signal symbols are added to the channel, according to Figure 2.5.

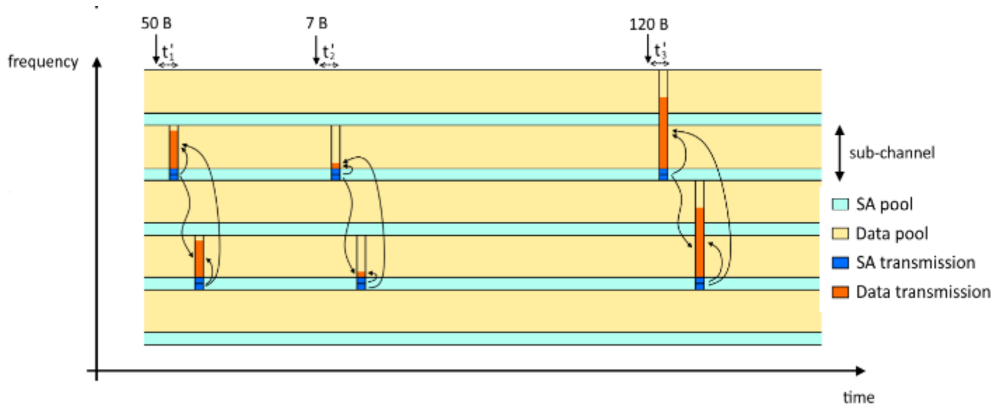
Figure 2.5. Reference signals disposition, from [20]



Secondly, to reduce latency and satisfy V2V requirements, in mode 3 and 4 the resource structure is changed in respect with mode 1 and 2. In particular the PSCCH contain the sidelink control information (SCI) also called scheduling assignment (SA), that is used by the receiver to know the organization of the radio resources in PSSCH. The SCI is transmitted identically, configured in format 0 for mode 1 and 2, format 1 for mode 3 and 4. The retransmission is mandatory because of lack of feedback channel in SL communication. The receiver can also implement the hybrid automatic repeat request (HARQ) by combining different redundancy versions of PSSCH transport block.

Focusing in particular on mode 3 and 4, we can say that PSCCH and PSSCH are separated in frequency. In fact the resource grid is split into many sub-channels, each one is divided into two parts: at the first resource block (RB) at lower frequency is placed the PSCCH and up above there is the PSSCH, composed by the other resource blocks in the sub-channel; this scheme is repeated in frequency over many sub-channels, as depicted in Figure 2.6.

Figure 2.6. PSCCH and PSSCH



In 3GPP release 15, frozen in March 2019, there are some PC5 interface enhancements that are backward compatible with services in release 14. In [21] they are described all the standardized enhancements:

- Carrier aggregation supported even for mode 4, with support of up to eight bands;
- Higher order of MCSs, including 64 QAM modulation;
- Maximum time beetween arrival at physical layer reduced from 20ms to 10ms;
- Radio resource pool sharing between mode 3 and mode 4;
- Transmit diversity using Small Cyclic Delay Diversity technique.

Moreover in the same technical report [21], some important new scenario are introduced. They are:

- Vehicle Platooning;
- Advanced Driving that enables semi-automated or fully-automated driving;
- Extended Sensors that enable the exchange of raw or processed data gathered through local sensors;
- Remote driving

These new scenarios have requirements reported in Table 2.1 and these KPIs are very important for what it is known as 5G V2X services or enhanced vehicular-to-everything (eV2X).

With these requirements we can state that release 15 is the first release that standardize some ultra reliable and ultra low latency (URULL) services. Moreover

Table 2.1. 5G V2X services requirements: [22]

5G V2X service	Packet size [Bytes]	Reliability [%]	Latency [ms]
Vehicle Platooning	300-400	90	25
Advanced Driving	2000	99.99	10
Extended Sensors	1600	99	100
Remote Driving	-	99.999	5

in release 15, 3GPP has standardized the 5G system phase 1 and thus the new radio specifications for 5G in the so called 'Non-Stand-Alone' (NSA) version. In these specifications they standardized the so called 5G new radio (5G NR), that is the radio access technology for the fifth generation mobile network. Among others, the most important novelties are the frequency bands use and the flexible numerologies.

5G NR uses:

- Frequency Range 1 (FR1) that include frequency bands above 6 GHz;
- Frequency Range 2 (FR2) that corresponds to bands between 24 and 100 GHz, the so called mmWave.

More specifically the FR1 covers spectrum from 410 MHz to 7.125 GHz and the supported channel bandwidth are 5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 90, 100 MHz. The FR2 covers spectrum from 2.425 GHz and 52.6 GHz and the supported channels bandwidth are 50, 100, 200 and 400 MHz.

Differently from LTE RAT, where possible bandwidth blocks are just 1.4, 3, 5, 10, 15 and 20 MHz, in 5G NR there are many channel bandwidth possibilities thanks to a flexible numerologies, or variable Sub-Carrier Spacing (SCS), fixed in LTE at 15 kHz, in 5g NR numerology changes. As stated in [21], a NR channel bandwidth is formed by a number of resource blocks, defined as "a consecutive series of 12 sub-carriers". Like in LTE numerology, in time domain radio frames are 10 ms long, composed by 10 subframes of 1 ms each. Nevertheless, in 5G NR in one subframe can fit one or more slots, depending on the sub-carrier spacing (SCS) as shown in [**?**]

Note that in case the cell has a large delay spread it is possible to use an extended cyclic prefix for sub-carrier spacing equal to 60 kHz; in that case in one time slot it is possible to send just 12 OFDM symbols and not 14 as usual.

An important feature introduced is that in TDD operation, each OFDM symbol in a slot can be used in downlink, uplink or in a flexible manner: in other words the scheduler can configure them semi-statically or dynamically.

Table 2.2. Multiple numerologies in NR (from [22], section 5.5.4

CP	SCS [kHz]	Slots per subframe	OFDM symbols per slot	Applicable frequency range
normal	15	1	14	FR1
normal	30	2	14	FR1
normal	60	4	14	FR1 and FR2
extended	60	4	12	FR1 and FR2
normal	120	8	14	FR2
normal	240	16	14	FR2

2.3.3 Release 16

In 3GPP release 16, they defined a new NR V2X that should coexist with LTE V2X, but it is not compatible, because the aim of NR V2X is to support those use cases with more strict requirements. While we are writing this thesis, the release is not frozen yet (March 2020 and target complention date in June 2020), but the NR V2X Study Item contain the following objectives:

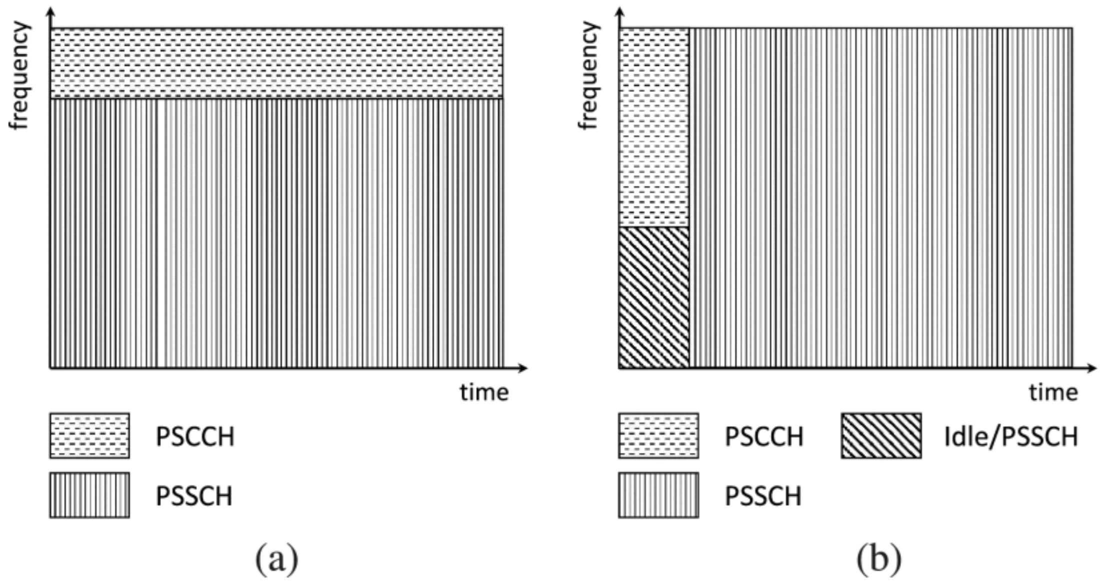
- C-V2X (as defined in rel. 15) coexistance with NR V2X in the same device;
- QoS management;
- Uu interface enhancements to support advanced V2X applications;
- RAT selection for a given V2X message optimized among LTE/NR Sidelink/Uu;
- Re-design of sidelink procedures to support advanced V2X use cases.

As described by [23], in release 15 new NR numerologies have changed the fixed structure of a subframe facilitating the latency reduction. The lower duration of a single slot allows the NR to reduce the number of reference symbols per slot. Moreover, the NR introduce the concept of slot scheduling, mini-slot scheduling and multi-slot scheduling. In LTE V2X a UE can transmit during the whole subframe (1ms) duration, but in case the packet size is small, a lot of time is wasted in this way. In addition in case the packet arrives from higher layer during the transmission sub-frame, the UE must wait the next slot to begin the transmission of new packet. All these cases can lead to resource inefficiency, for this reason NR also support mini-slot scheduling: UEs with latency-critical messages can schedule the beginning of transmission at any OFDM symbol within the slot without waiting next transmission slot. Moreover, thanks to a mechanism called slot-aggregation, UEs can combine more slots forming a multi-slot, useful in case of large-size packets.

As seen before, in LTE V2X PSCCH and PSSCH are multiplexed in frequency, as shown in Figure 2.7 (a). In NR V2X instead, the PSCCH is separated in time by

PSSCH: control information are sent before PSSCH transmission, so that a receiver can decode the message exactly when the transmission finish, not necessarily at the end of the sub-frame as in LTE V2X; in this way NR V2X can satisfy tighter latency constraints. In Figure 2.7 (b) is illustrated the multiplexing in time, where, as [23] points out "the use of resources marked as "Idle/PSSCH" is still under consideration and can be left idle or used for the transmission of PSSCH".

Figure 2.7. PSCCH and PSSCH in LTE V2X and NR V2X (from [23])



One key mechanism introduced in NR V2X is sidelink feedback channels. Even if LTE V2X supports re-transmission, they are blind, or in other words, the retransmission are performed both in case the receiver effectively receive the packet or not. This re-transmission mechanism is fundamental to guarantee some reliability. The introduction of Physical Sidelink Feedback Channel (PSFCH) can provide higher channel efficiency, higher channel state information leading to better reliability.

Like LTE V2X release 12, NR V2X defined 2 modes: the first one allow direct communication within gNode B coverage, while the second mode support communication completely independent from gNode B. Differently from previous releases, NR V2X Sidelink introduce new 4 sub-modes that distinguishes mode 2:

- Mode 2a: similarly with C-V2X sidelink mode 4, each UE selects its resources autonomously, considering sensed information;
- Mode 2b: UE can assist others to select resources, ;
- Mode 2c: UEs select resources using pre-configured grants;

- Mode 2d: special UEs select resources for themselves and for other UEs, mainly used for group communication for applications like platooning .

In further 3GPP meetings mode 2b and 2c are abandoned as separate sub-modes because mode 2b features can be used in modes 2a and 2d, while the pre-defined patterns can be used in mode 2a.

What was thought in mode 2b - that can be exploited as well both in modes 2a and 2d - is the possibility by a user, for example the receiver, to notify the preferred resource elements using PSFCH. In mode 2a, every user can sense the PSFCH to gather information about other UE preferred resource so that each user can choose the best resources. The main limitation of this approach is high complexity in case of high density scenario. In mode 2d a UE can perform resource allocation for itself and for the rest of the group. This sub-mode is useful in group application like platooning. The user that perform resource allocation for the members of the group is called scheduling UE (S-UE). This mechanism is beneficial to the group, because it can reduce the number of collisions within the group. The main issue of this mode is the definition of S-UE: one proposal sees the S-UE be a pre-configured vehicle, but this would imply additional hardware/processing capabilities for certain vehicles. Another proposal sees a geo-location based choice, in particular a vehicle in the middle of the group could have better radio information of all other members of the platoon.

2.4 C-V2X schedulers

In order to meet requirements, one of the most important element in the transmission chain is the scheduler. In the following sections we describe the scheduler standardized by 3GPP for LTE V2X mode 4 and some of our proposals that can be used as comparison to understand which one better fit the requirements for C-V2X services.

The first scheduler is called semi-persistent scheduler, while the others are the self organizing TDMA and the optical orthogonal codes.

2.4.1 Semi-Persistent Scheduling (SPS)

Because of periodicity and predictable packet size in V2X communication, 3GPP has proposed a standardized scheduler called semi-persistent scheduling (SPS) that is sensing-based. Its aim is to optimize the resource grid and minimize transmission collisions among different users.

As described in [24], in semi-persistent-scheduling every user transmits packets in a certain slot every resource reservation interval (RRI). A counter is linked with each transmission and it is called SL_RESELECTION_COUNTER. Every transmission this counter is reduced by one by the user MAC entity. When the counter reach zero, the user would reuse the same resource with probability p_{RK} (probability resource keep) or would reselect a different resource with probability $1 - p_{RK}$. In any case the user would extract an integer value randomly selected among the range C1 and C2 in uniform distribution. These two parameters depends of course by the RRI value, according to Table 2.3. If the reselection choice is taken the user generate some resource candidates inside the selection window.

Table 2.3. SL_RESELECTION_COUNTER range, depending on RRI value: [24]

RRI	[C1, C2]
>= 100ms	[5,15]
50ms	[10,30]
20ms	[25,75]

The selection window is a set of subframes in advance in respect of current subframe by T1 and T2. T1 depends on the user process delay, while T2 depends from system requirements. Resource candidates are generated in function of what was sensed in the sensing window, whose length is of 1000 ms. The resource is selected uniformly randomly among the resource candidates.

In case two users selects the same time-frequency resource for transmission, the collision cannot be avoided, but neither detected by either users. A bad feature of this scheduler is that in case of collision, it would persist over multiple messages without the user know about the collision. Furthermore, because of standardized message frequencies, the probability of users select same messaging interval increase. For this reason the algorithm is not persistent but semi-persistent.

Analytical model and analysis In 2018, Manuel Gonzalez et al. published [25], where they explored the analytical model of C-V2X mode 4 and performances for a semi-persistent scheduler.

Initially the paper introduces the physical layer related to mode 4 and they it explains the scheduling algorithm, defining variables like λ the packets transmitted per second per vehicle, the probability of reselection when the counter reach 0 p_{res} as well as $d_{t,r}$: the distance among transmitter and receiver. Then the paper consider all possible sources of error and quantifies them probabilistically. $\delta_{HD} = Pr(e = HD)$ is the probability that the error come from half duplex impairment: this error happen when a user cannot receive a packet because that user was transmitting at that time slot. $\delta_{SEN} = Pr(e = SEN|e \neq HD)$ is the probability that the error is due to receiving power below a threshold P_{SEN}, excluding half duplex impairment. $\delta_{PRO} = Pr(e = PRO|e \neq SEN, e \neq HD)$ is the probability that the received power is higher that P_{SEN}, the half duplex impairment is excluded, $\delta_{COL} = Pr(e = COL|e \neq PRO, e \neq SEN, e \neq HD)$ is the probability that another user has transmitted on the same time time slot, excluding the previous errors.

The paper expands the previous formulas, exploring the sources of error. For example the half duplex impairment depends just by the number of transmitted packets by each vehicle and the number of sub-frames within a second,

$$\delta_{HD} = \frac{\lambda}{1000}$$

Then, the sensing error

$$\delta_{SEN}(d_{t,r}) = \frac{1}{2}\left(1 - erf\left(\frac{P_t - PL(d_{t,r}) - P_{SEN}}{\sigma\sqrt{2}}\right)\right)$$

depends from the path loss and TX-RX distance, the transmitted power P_t and the receiving power threshold P_{SEN}.

$$\delta_{PRO}(d_{t,r}) = \sum_{s=-\inf}^{+\inf} BL(s) \cdot f_{SNR|P_r>P_{SEN},d_{t,r}}(s)$$

where

$$f_{SNR|P_r>P_{SEN},d_{t,r}}(s) = \begin{cases} \frac{f_{SNR,d_{t,r}}(s)}{1-\delta_{SEN}}a & \text{if } P_r > P_{SEN} \\ 0 & \text{if } P_r \leq P_{SEN} \end{cases}$$

is the PDF of the SNR experienced at a distance $d_{t,r}$ for values greater that P_{SEN}, and $BL(s)$ is the BLER for SNR equal to s (these values come from look up tables). Finally the probability of error due to collision is

$$\delta_{COL}(d_{t,r}) = 1 - \prod_i \left(1 - \delta^i_{COL}\left(d_{t,r}, d_{t,i}, d_{i,r}\right)\right)$$

where

$$\delta^i_{COL}\left(d_{t,r}, d_{t,i}, d_{i,r}\right) = p_{SIM}\left(d_{t,i}\right) \cdot p_{INT}\left(d_{t,r}, d_{i,r}\right)$$

is the probability of packet loss due to a collision with vehicle i, and it depends from the probability that user i and user t transmit simultaneously on same resources and from probability that of interference with user i on the receiver, due to higher received power from packet transmitted by user i in respect with that one transmitter by user t.

Finally, in the paper this model has been validated by simulations in Veins and OMNET++, using SUMO for traffic simulation. The results state that the mean absolute deviation of the model from the simulation is always below 2.5%, so the model can be seen as valuable tool to further investigate behaviour of C-V2X mode 4 under different scenarios and parameters.

2.4.2 Self-organized Time Division Multiple Access (STDMA)

Self-organizing TDMA (STDMA) is a protocol based on MAC layer. As stated in [26], it is used in shipping (Automatic Identification System, AIS) and in airline companies for his periodical structure. Because his tested on field effective, Eurepean Telecommunication Standard Institute (ETSI) has considered STDMA a good alternative to Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).

STDMA structure is composed by slot, whose dimensions, in terms of duration and bandwidth, depends from the fixed packet size. N slots form a frame, that is repeated periodically in order to support periodical transmission. The parameter N depends from the application, from packet size and transmission parameters: fixed N, the channel capacity is determined. It is also assumed that all the users are slot-synchronized, but frame-synchronization is not required.

The STDMA protocol is based on slot reservation, so each user would transmit during his slots time and would receive during the others slots. In order to avoid collision, the protocol need to determine which slots each user can use to transmit. The protocol consists of four phases:

1. initialization phase;
2. network entry phase;
3. first frame phase;
4. continuous operation phase;

Initialization phase During the initialization phase, the selected user, before enter in the system, need to listen the channel for one entire frame and assign to every slot a state depending on what they receive during each slot duration. The listening starting point depends from the user startup, so it is random. The possible slot states are:

- Free slot;
- Internally allocated slot;
- Externally allocated slot;
- Unavailable slot.

Free: the slot is unused by any other user within range.
Externally Allocated: the slot is used by an other one user within range, with a power level received above the Clear Channel Accessment (CCA) threshold.
Internally Allocated: the slot is used or reserved by the current user.
Unavailable: the slot is used by an other user but the received information cannot be decoded correctly.

Is important to notice that during the initialization phase, the state "internally allocated" is impossible to find because no packets are scheduled yet. It must be noticed that a slot can be assigned the state "Unavailable" when a collision occur. We assume that the user during the following phases would continuously update the slot states, monitoring them during the receiving time. Once the selected user has listened all the N slots and has assigned to each one a state, it follows with network entry phase.

Network entry phase In network entry phase the current user should transmit a Network Entry Packet (NEP). This packet is sent just once and it's aim is to inform other users within range that a network joining is occurring. The NEP is trasmit in a free slot chosen randomly according to Random Access Time-Division Multiple Access (RATDMA) protocol, because the slot is used without pre-annuntiation. In this phase two parameters are defined: the Candidate Set and Nominal Transmission Slot. The Candidate Set (CS) is the set of all free slots. The Nominal Transmission Slots (NTS) is the set of slots chosen from the algorithm to actually transmit the packets, at this step it coincides with the NEP. The last part of this phase is to choose the NTS among CS for the first transmission. In order to do so some steps are required:
a Nominal Increment (NI) is defined as NI = N/Rr the ideal interval between two consecutive packets;
a Nominal Starting Slot (NSS) is defined and it is randomly chosen slot among CS;
a Selection Interval (SI) is defined and it is the set of slots centred around NSS, whose cardinality depends from variable parameter s, that is the ratio of the length of SI and the length of NS and it is lower or equal to one.

After have defined SI, CS is compiled adding at first all free slots, then adding some externally allocated slots in case the CS minimum size is not reached using just free slots. It has to be considered that externally allocated slots are adding starting from those used by further users in respect of current user. Once defined CS, the NTS is chosen randomly with uniform probability over all CS. It must be noticed that in case the NTS correspond to an external allocated slot, some collisions would be possible. Once the NTS is chosen, the user can transmit the NEP, adding the offset between the NEP slot and the NTS slot and it would enter in first frame phase.

First frame phase The main aim of first frame phase is to reserve all successive NTS to satisfy the user communication. If the first packet was reserved by previous phase, the other r-1 NTSs must be decided before transmitting the first packet. In the first packet would be attached a timeout t_0 to the NTS 0 and an offset to reserve the NTS 1. The timeout is used to reserve NTS 0 slot in the consecutive frames, so at every frame, at that timeslot, the timer would be decreased of one time unit. When it reaches 0, a new slot must be reserved according to procedures reported in

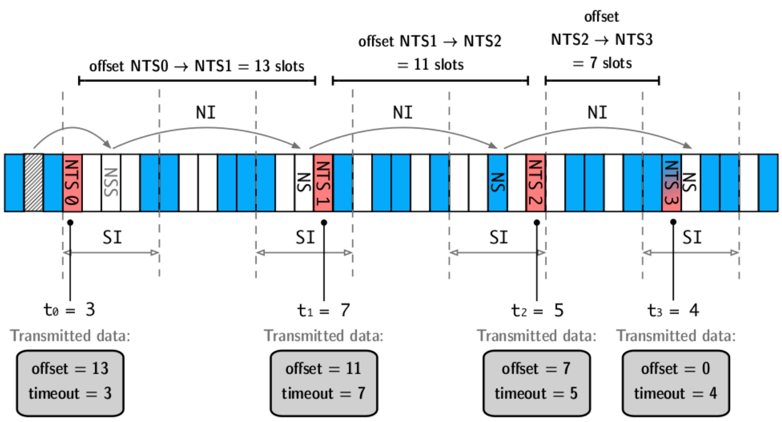
Table 2.4. STDMA system parameters: [26]

Symbol	Name	Description
NSS	Nominal Starting Slot	Slot around which is build the SI for the first NTS
Nominal Slot (NS)	Nominal Slot	Slot around which is build the SI for any NTS subsequent the first; NSS is the first NS
NI	Nominal Increment	Ideal inter-distance (in slots) between two consecutive transmissions. it is equal to the ratio between the number N of available slots per frame and the Report rate (Rr)
Rr	Report rate	Number of transmissions per second the current UE needs to perform
SI	Selection Interval	The set of slots surrounding the NTS or the NSs among which slots that compose the CS are chosen
NTS	Nominal Transmission Slot	The slot chosen by the UE to perform a packet transmission
t_{min}	Minimum timout	Minimum value to which the timeout counter can be initialized
t_{max}	Maximum timout	Maximum value to which the timeout counter can be initialized

continuous operation phase. The timeout initial value is picked randomly uniformly between t_{min} and t_{max}.

To reserve the next NTS, similarly as the previous phase, a NS 1 is selected in NI slots following the NSS, then the SI is construct around NS, the CS is compiled as previous phase and NTS 1 is picked randomly within CS. At this point the first packet is transmitted and it would contain the timeout t0 referring to NTS 0 over next frames and the offset in slots from NTS 0 to NTS 1. Doing so, all the users that receive correctly the packet, can set the NTS 0 slot to the state externally allocated, as well as the user would set it as internally allocated. This procedure is repeated for r-1 times, until all r NTS are allocated. After the last transmission, the user moves to the continuous operation phase. The picture section 2.4.2 represent an example of first frame phase

Figure 2.8. STDMA parameters



Continuous operation phase The selected user enters in this phase when it is in steady state, so it has entered in the network, it has reserved his slot, it is aware of other user reservation and other users are aware of his reservation pattern. In this phase, the user transmits a packet in the NTS slot, decreasing the associated timeout before the transmission. When the timeout reaches 0, a new NTS is reserved, following the same mechanism as before, and in the next packet it would be attached the offset and timeout associated.

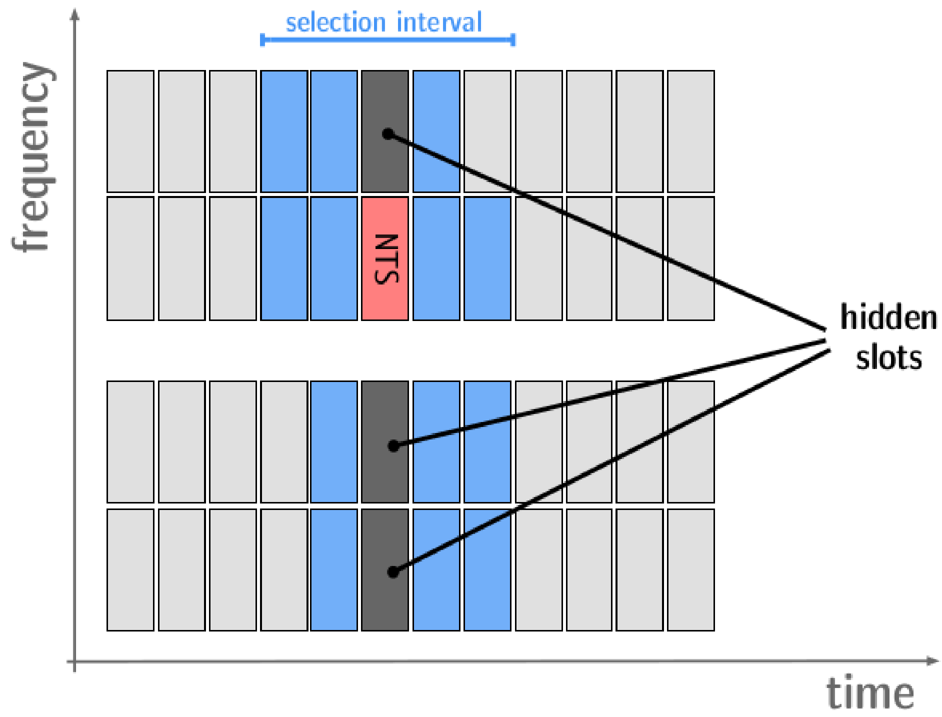
It must be noticed that in this phase, the use of offset change from previous phase. If before it represented the number of slots for NTS i+1 from NTS i, in this phase it indicates the offset related to the same NTS but in the next frame. In order to distinguish this two differences, the timeout is set to 0. So when the timeout reach 0, the relative offset is reserving the NTS in the next frame.

Analytical model and analysis As seen in LTE physical layer description, the physical structure is characterized by several subchannel in frequency. Due to antenna limitation, a transmitting user is not able to sense the all the slots located at NTS slots.

This phenomenon is called by the authors "HD impairments" and due to this phenomenon a new slot state must be introduced: hidden slot, that are those slot that cannot be received/sensed because located during user transmission. So a new source of loss must be considered because of HD impairment, because of possible collisions.

In order to avoid HD effect we could extend the STDMA protocol into the OFDMA deployment (OSTDMA). The OSTDMA simply deal with possible collisions due to hidden slots removing these slots from CS during re-reservation definition. The current slot is however hold because other users would not select it before knowing the re-reservation parameters of the current NTS.

Figure 2.9. OFDM Self-organizing TDMA



This method uses a lot of resources, so it would work well when the channel load is low, but in high channel load it would create collisions from other sources. In order to have better slot efficiency the author proposed the selective hiding STDMA (SH-STDMA). This second proposal assign a penalty to the SI higher if the distance among the user occupying a slot in the SI is nearer the receiver. In this way, when the CS must be compiled, free slots are added starting from subframes with lower penalties, or in other words, the algorithm selects slots externally allocated by users that are the furthest in mean from the receiver.

As expected the results in simulations shows that OSTDMA works better for lower channel load, but with higher channel load the SH-STDMA is better. So, in function of the channel load considered in the scenario, we choose one or the other proposal.

2.4.3 OOC codes

Optical Orthogonal Codes (OOC) are a family of (0,1) sequence that has some special characteristics that were exploited for the first time in applications like code division multiple access (CDMA). It is possible to create a long set and then chunk it into (0,1) sequences called codewords. As described in [27], the codes satisfy the autocorrelation property and the cross-correlation property: the auto-correlation of each codeword in the OOC has a strong peak at $\tau = 0$, and very low elsewhere and cross-correlation between any two sequences remains low. In particular given any pair of codewords u and v, from the same OOC set and with length L and given a threshold λ holds the following inequality:

$$\sum_{j=1}^{L} u_j \cdot v_j \leq \lambda \quad \forall u \neq v$$

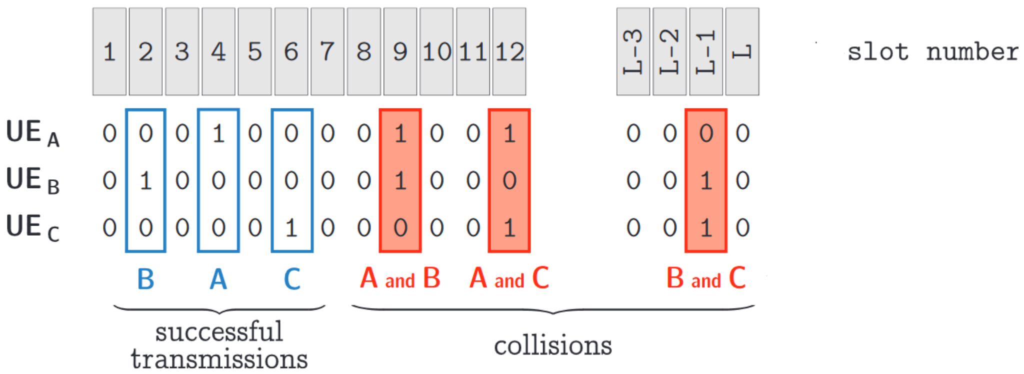
Another important property of these codes is their periodic correlation, if we take cyclic shift of codewords from an optical orthogonal codes, the correlation properties are not affected.

The previous properties allow detection of desired signal reducing at minimum the interference with unwanted signals in the medium. For this reason, optical orthogonal codes are also used in those applications where low interference is a key element like mobile radio, radar and sonar signal design or frequency hopping spread spectrum communications.

As the author explain in [28], if we associate the bit 1 to UE's TX mode and bit 0 to UE's RX mode, each UE can generate an OOC codeword with same parameters of other users, exploiting optical orthogonal codes as a distributed resource scheduling. In fact, if every bit of the sequence is linked with a time slot, each user can transmit or receive packets corresponding of its codeword. Then, in order to deal with collisions and guarantee some reliability we could assume a retransmission - corresponding to the Hamming weight w - equal for all users in the defined period. In this context the previous inequality is useful because λ denote the maximum number of collisions that the code allow, so choosing $\lambda < w$ we can increase reception probability. The drawback of this property is that it limits the number of possible codewords belonging to the same OOC codeset. In subsection 2.4.3 is shown an example where $\lambda = 1$ and $w = 3$.

It is important to notice that this scheduling approach is blind and static, so once the codeword is generated, it remain the same for all the duration of the defined period and each user is not aware of concurrent users transmitting pattern.

Figure 2.10. Distributed allocation: OOC-based access to slots (from [28])



Chapter 3

Analytical study and simulations

In this chapter we describe the scenario we have used in simulations. All parameters are provided and all possible topologies are described, in such a way we can describe how a perfect scheduler should perform, so that we can than compare with performances given by semi-persistent scheduler and self-organizing time division multiple access scheduler. After this theoretical analysis, we briefly introduce the network simulator we have used. After the simulator description, we describe how the workflow has been modified during the internship and which issues we have encountered. After we expose simulation results both in NS3 and MATLAB, with comments about results.

3.1 Perfect scheduler analysis

The scenario used is the depot, wherein we assumed 200 consists, organized in 10 tracks with 20 consists each. Every track is spaced of 2 meters, each consist is 26m long and spaced in respect to the next one 1 meter, for a total track length of 269m. Each consist is 3 meters large.

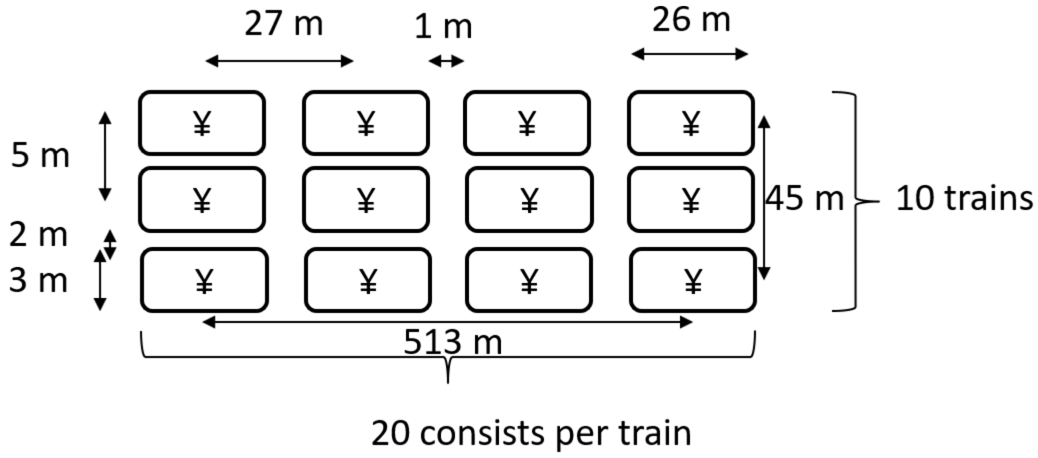
The speed inside the depot is negligible, so that it can be excluded any significant Doppler effect, but path loss and shadowing effect have to be considered.

In the depot there are many consists, so high load is expected, and two phases: track creation, during which consist inside the same track as well as consists belonging to different tracks would communicate, and track management where just consist of the same track would communicate.

Exchanged packets are 1432 bits as packet size and they are transmitted every 40ms.

There are two different possible topologies: mesh network and linear network.

Figure 3.1. Consists in the depot



In the former topology the antenna is placed on the roof of the consist, the communication can be with with every other consist in the transmission range. On the other side in the linear topology, consists have antennas placed at the beginning and at the end and they can communicate just with the consist next to them. The two configurations have pros and cons. On one hand mesh network has the pros of being able of communicate within the whole depot without any relay. Moreover, this option is cheaper, because just one antenna per consist is enough for the communication. The cons with mesh topology is that this kind of communication is strongly affected by interference and it means lower reliability of each transmission. On the other hand linear topology has the advantage of having very good channel quality, that it reflects in better reliability per hop, but as a clear disadvantage the protocol must support multi-hop communication and not less important, the entire system is much more expensive because each consist must have two antennas.

Considering a BPSK transmitted symbols, two bits for each resource element are transmitted. Considering a normal cyclic prefix we would have seven resource elements per resource block and 12 sub-carriers, so in a RB we would send 2*7*12=168 bit. To this quantity we need to consider that some resource elements are occupied by four reference signals (RS) or pilot symbols, so in a RB we can send just 164 bit. The packet size is 1432 bit, so it would need 1432/164 = 9RB plus one dedicated for the sidelink control information (SCI). 10 resource blocks occupy $10RB * 12 * 15kHz = 1.8MHz$, so it means that in 0.5 ms it can be scheduled five users at the same time. The five transmitting users cannot transmit and receive at the same time because of half duplex impairment, so it means they must transmit at least twice. This assumption is perfectly applicable to fight channel variation and lack of feedback scheme. It means that the five users would receive just one time the packet for the other transmitting user in the current time slot, but all the other receiving users would receive the packet twice.

According to specification, each user would receive from higher layers a packet to transmit periodically, it means that in that interval the scheduler must serve all users twice. In particular, following our scenario, every 0.5 ms the scheduler can allocate five users at the same time for 40 ms, it means that the scheduler has 2slot per ms $*$ 40ms $*$ 5users = 400 time-frequency slots to assign. In the specific scenario, we should schedule 200 users, that transmitting two times need exactly 400 transmission slots.

A perfect scheduler would allocate user according to the following scheme: if a slot is free allocate a new user in that slot and in the first free time-frequency slot in a time-set not yet occupied by any other users already scheduled in the current time-set. The Table 3.1 would better clarify the scheme: in the first time slot the first five users are allocated at different five sub-channels in the frequency domain, then in the second time slot other 4 users are scheduled and one user of the previous set is rescheduled, in such a way its information can be received by the four users belonging to the previous set. In the third time slot other three new users are scheduled plus one user of the first time slot set and one user of the second time slot set and so on and so forth.

Table 3.1. Time frequency allocation in a perfect scheduler

1	1	2	3	4	5
2	6	6	7	8	9
3	7	10	10	11	12
4	8	11	13	13	14
5	9	12	14	15	15

It must be notices that the scheme would repeat exactly every 6 time-sets, so it means that if the total time-frequency slots is not a multiple of 6, some users cannot transmit twice. If we need to sacrifice some transmissions, the scheduler could avoid to send a message that a very far user has not received yet, because even in case of transmission the further distance could effect the good reception of the message anyway. For this purpose, the scheduler could assign a increasing number starting from users in the centre of the system and then at higher and higher distances, such that the very last users that must be scheduled at the end of the 40 ms are the furthest users. It must be considered that because of different received power some messages cannot be decoded by all users, but for sake of simplicity we would consider same received power at all receiving users. In the real world this scheduler can be implemented in case an eNodeB would assign each user to each time-frequency slot. In that case the sidelink channel used would be the mode 3. This option is indeed probable because in a depot, there is the possibility of the presence of a eNB.

In case the eNB is not present in the depot, all the consists must autonomously coordinate following a semi-persistent scheduler or a STDMA scheduler.

3.2 Network Simulator and workflow

NS-3 is a discrete-event network simulator, targeted primarily for research and educational use. NS-3 has been used because it allows users to run real implementation code in the simulator.

Initially, one of the scopes of the internship was to upgrade some provided codes written in some older NS-3 versions, like NS-3.18 and NS-3.22 up to version NS-3.30. The main reason was that newer version provides more functionalities and the corresponding simulations would have been more realistic. The main objective was to have a stable newest version of the simulator, implementing LTE V2X feature. Upon that, the next step would be to change the LTE V2X scheduler and implement a different scheduler based on self-organizing time division multiple access.

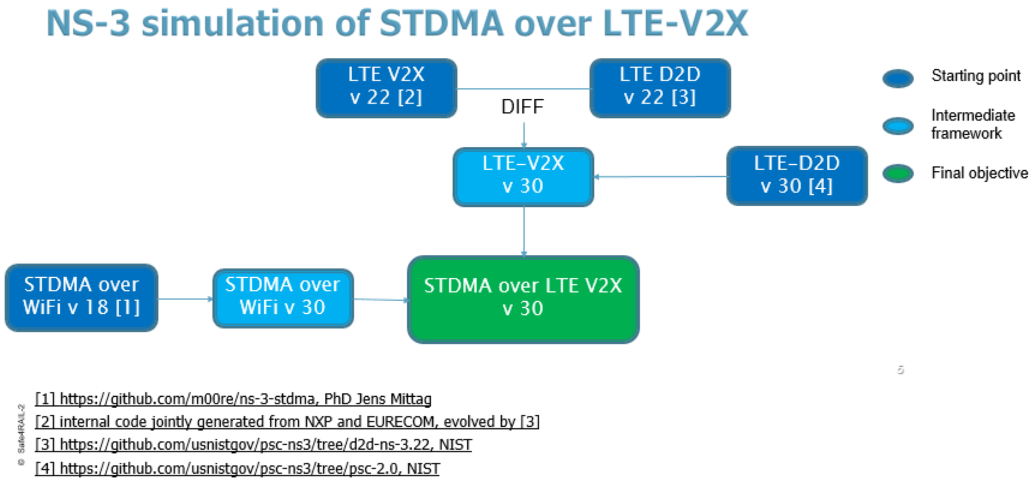
The starting point was a NS-3.22 code of the implementation of LTE D2D, on the same version a code implementing LTE V2X was provided. The workflow was to start from the LTE V2X version and update it to version 30.

The first errors came by the new compiler: old codes are compiled by old compilers, but nowadays new compilers have more strict rules in order to prevent errors inside the code. Other source of errors was that from past versions of network simulator to version 30, many structures are changed, so during the compiling phase, many variables cannot be created because those structures did not exist any more in the new version of the simulator. Fixing these kind of errors were difficult because sometimes some structures change radically where the simulator intended to save variables, so we were stuck.

In the meanwhile, the national institute of standard technology website published a version of network simulator 3.30, implementing the LTE D2D. At this point, the workflow was modified: starting from NS-3.30 implementing LTE D2D, I would have to use the linux command *diff* among the two implementation of LTE D2D and LTE V2X both in version 3.22, to generate the updated version of LTE V2X running on network simulator version 30. Practically, we were meant to modify the new code following the modifications were made in the older code to implement the V2X feature. *Diff* command shown some changes in the two codes, like the scheduler, the physical layer module and some helper to deal with new object that were created. For a better comprehension the Figure 3.2 explain the main objective. The main issue was that many modification were done on data structure in the old simulator version that are no more existing in the new one of the simulator, so the most complex part was to understand which data structures were change, how to apply modification from old data structures to new ones.

Unfortunately, these issues stole a lot of time and the limited duration of the internship forces the workflow to redirect efforts in different direction again. The

Figure 3.2. Workflow representation



new aim of the internship became to investigate the semi-persistent scheduler in old version of NS-3.22 and compare the performances with the optical orthogonal codes scheduler using an implementation in MATLAB as a simulation.

Indeed, as came from [26] and can be observed in Figure 3.3: in low channel load and very high channel load, optical orthogonal codes have better performances then STDMA. For this reason, it sounds reasonable explore how OOC performs in respect with semi-persistent scheduling.

3.3 Simulations

For each simulation, the variation over density and inter-consist distance is analysed, because the main scope is to observe if there is a possible scenario to meet requirements. Moreover, a dedicated investigation over distribution is performed, in such a way to verify requirements in terms of probabilities. Furthermore, a variation over different packet size is made to see if some observation can be made with that parameter, both for fixed size or with variable packet size, following a gaussian distribution and finally varying the modulation used.

3.3.1 Simulations using semi-persistent scheduler

The following simulations are performed considering a mesh topology, with antennas placed on top of the consist and being able to communicate with all others antennas. The simulation select each consist as transmitter, and then sense the condition for every receiver, placed at a certain distance. When all consists are chosen as transmitter, the program estimate a mean value of parameters in function of

Figure 3.3. Comparison between STDMA and OOC taken from [26]

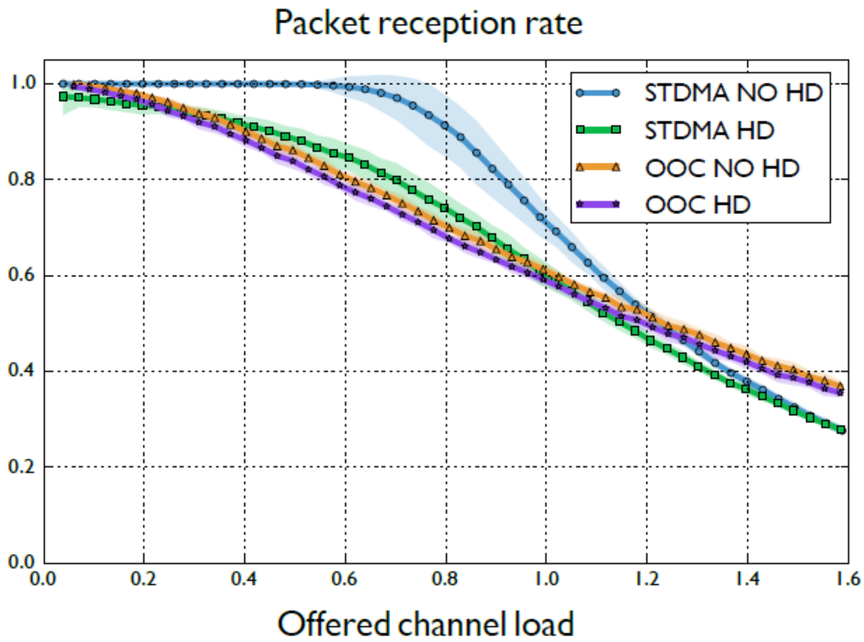


Figure 11: STDMA and OOC comparison with and without HD impairment. The shaded area around the curves represents the 95% confidence interval

distance among transmitter and receiver.

Semi-persistent scheduling over density In figure 3.4 the first feature it can be noticed is that independently by the simulation density, the performances don't change. This fact lead to the conclusion that the channel has enough capability to sustain all transmissions in the scenario.

The second important observation is about the points where distance is high: they do not follow the normal behaviour. The reason can be found in the so called "border effect". Indeed, the only consists that are so far apart are those at the limit of the depot, and for those consists, the channel has more capacity, so they have better performances.

Another important observation must be done around network topology. As described before, the simulation are performed varying inter-antenna distances. The antennas are thought to be placed on the top of the consists in a mesh topology, so that all of them can communicate with every other consists. But as shown in 3.4, performances become very weak when the distance exceed half of the depot area.

Figure 3.4. PRR for different inter-antenna distance

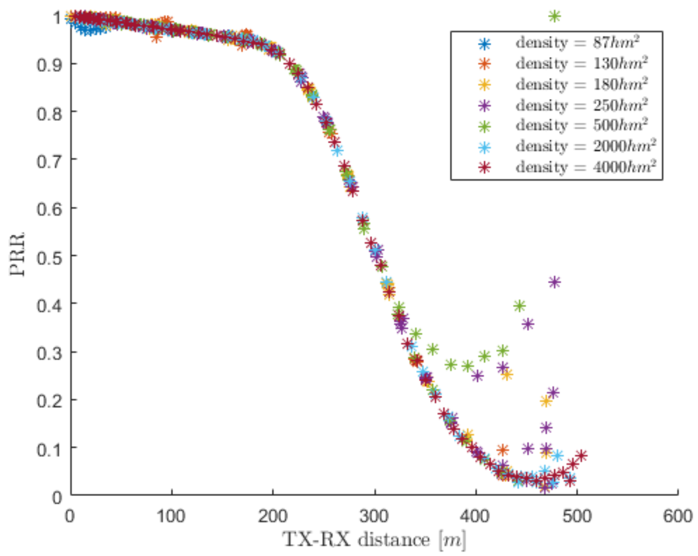


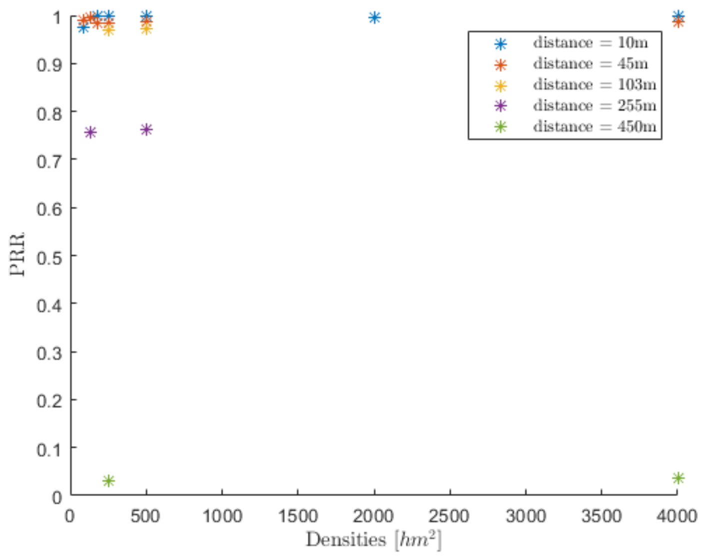
Table 3.2. Conversion from density and inter-antenna distance

density $[veh/hm^2]$	inter-antenna distance $[m]$
87	444
130	74
180	37
250	25
500	17
2000	12
4000	9

Having this information in mind, seems reasonable to allow a multi-hop communication and reduce the antenna range capability. For example, if we would place the antennas on consists like in a linear topology, antenna distance became 10 meters. At that distance, the PRR is very high, so it would provide higher reliability.

Semi-persistent scheduling over distance In Figure 3.5 can be observed that the PRR is independent from density of antennas, but just the TX-RX distance affects performances. In other words, it means that the system can handle properly all consists inside the depot, just shadowing effect and propagation affect transmission in this configuration.

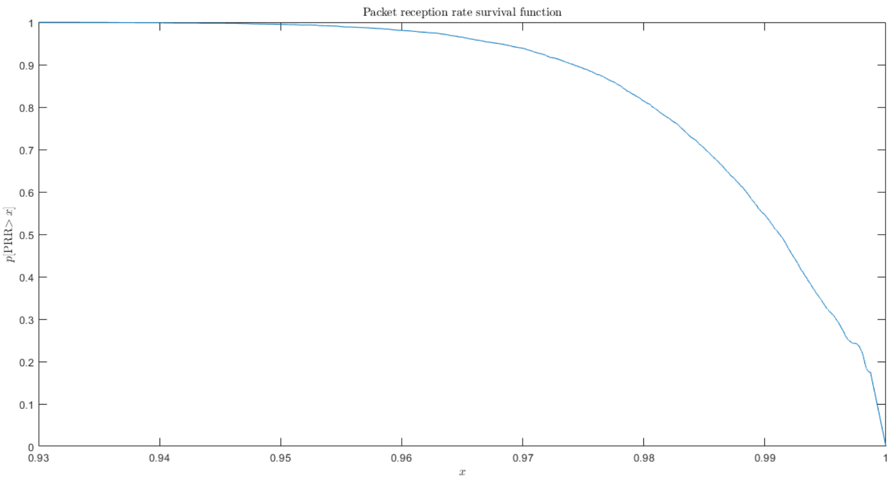
Figure 3.5. PRR over density for different TX-RX distance



Semi-persistent scheduling distribution probability InFigure 3.6 it is shown the survival function of received packets, or in other words, it is shown the reliability of a packet to be received. In particular we have shown a density of 250 veh/hm^2, that corresponds to 200 consists in the depot, spaced by 2 meters among consists and 28 meters among consecutive antennas, in a mesh topology. If we look the reliability at a TX-RX distance of 10 m, we can see that we are sure the PRR is greater then 96%, but then the probability decrease quite fast. It must be noticed, that inter-consist distance is 2 meters, so if we observe from simulation at which point the probability degrade, it is around 99.95%. This quantity is still far from requirements for TSN, but it is a good improvements if we would use a linear topology, in which antennas are placed in front and in the back of each consist, and a better per-hop communication can be reached.

Semi-persistent scheduling over different fixed packet size Considering a fixed packet size, we can observe in Figure 3.7 that we have same performances for some packet dimensions. As we can see, just three lines are shown because the others are overwritten, as they are exactly the same. So packet size of 15 bytes and 50 bytes have the same performances of a size of 100 bytes, then 179, 200 and 300 bytes have the same performances. This behaviour can be explained by the fact that some padding is inserted inside a packet, so until the size doesn't reach the threshold, performances doesn't change. This behaviour is important to observe because if the packet size is around the padding threshold, it can be considered to reduce a bit of information in order to get higher performances, or in the opposite

Figure 3.6. Reliability for density at $250veh/hm^2$ and TX-RX distance at $10m$



case, include more information that would not affect the transmission.

Semi-persistent scheduling over variable packet size It is possible that the system may work with fixed packet size, but sounds reasonable that the application sends some small packets as well as big packets. For this reason we have studied the behaviour of the system, in case of a variable packet size, statistically distributed as a gaussian with mean equal to 340 bytes and a standard deviation of 100 bytes. In other words, the 95% of packet sizes are between 140 and 540 bytes. Results are shown in Figure 3.8.

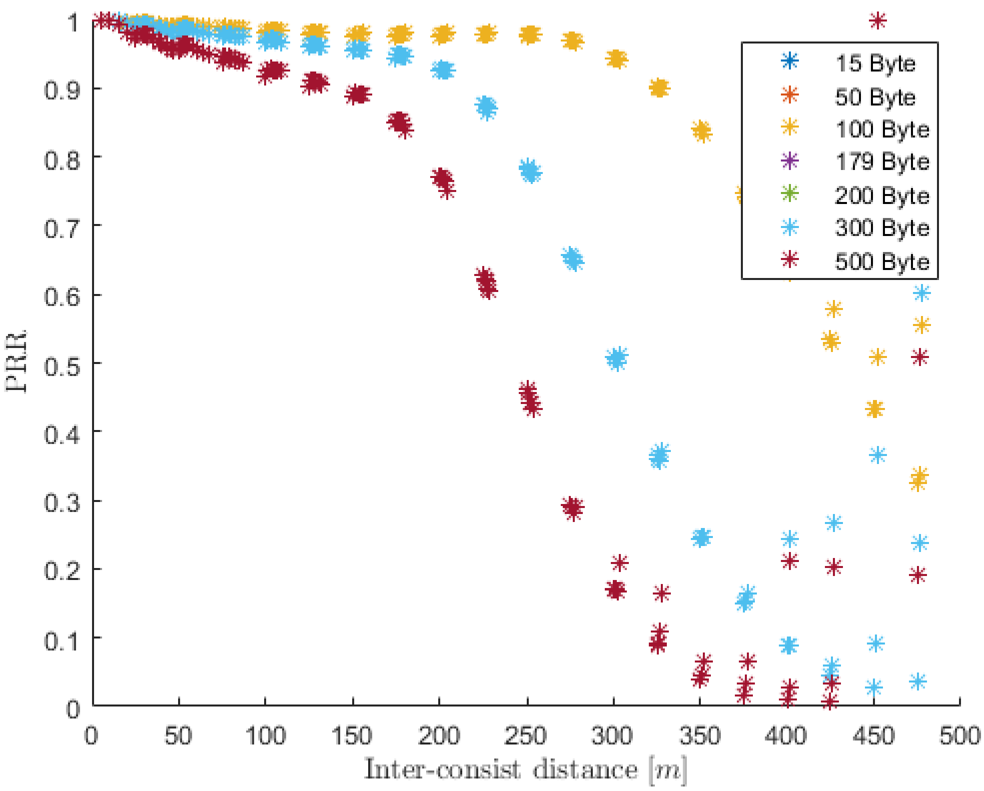
We can observe that for short distance the system has very high probability of reception: 99.9% for distance before 15 meters. then it slowly decrease to 99% until 200 meters and then decrease steeply. The steep decrease at 200 m is reasonable looking at the behaviour for fixed packet size at 300 bytes, but what is much better for variable packet size is the performance for lower distances, that before was around 99% for small packet size and small distance.

3.3.2 Simulations using optical orthogonal codes

In the following sections we describe the behaviour of the system using optical orthogonal codes in conditions as similar as possible to previous scenario, in order to be comparable. Unfortunately, the codes are extremely different so some difference must be reported.

First of all, the scenario is no more a 2D depot, but it is more a 1D line, where one transmitter at the centre of the line send a message, and all the consists inside

Figure 3.7. PRR for different packet size



the receiving range receive it. The receiving range is the same as the depot scenario: the hypotenuse of the 2D depot whose length is 514 m.

Secondly, the code just test the behaviour of the system at layer 2, so the physical layer is completely ignored, that's why, as we describe later, the performance does not change over distance: no path loss or shadowing effects are considered, but just collisions.

It must be noticed that all consists in the range, check if the transmitting slot corresponds to a slot already occupied by other consists - this case would lead to a collision - or occupied by themselves - leading not to receiving it because of half duplex hiding.

Lastly, because this is a linear topology, the density is specify in vehicles/km, differently as before, but the number of vehicles in the system remain compatible with previous scenario.

OOC scheduling over density Regarding Figure 3.10, the first observation is about how the system reacts when we change the density. As we can see, the PRR

Figure 3.8. PRR over gaussian distributed packet size

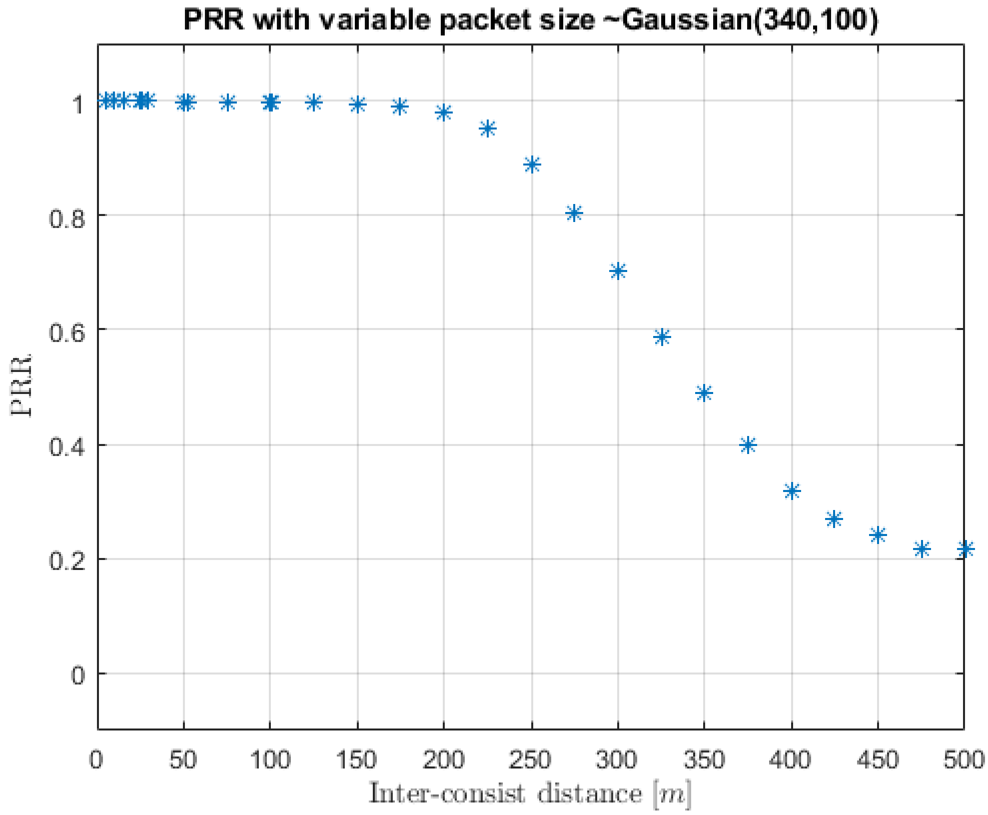
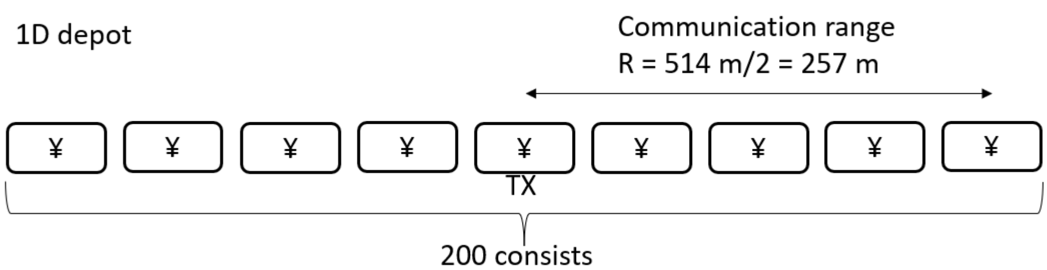


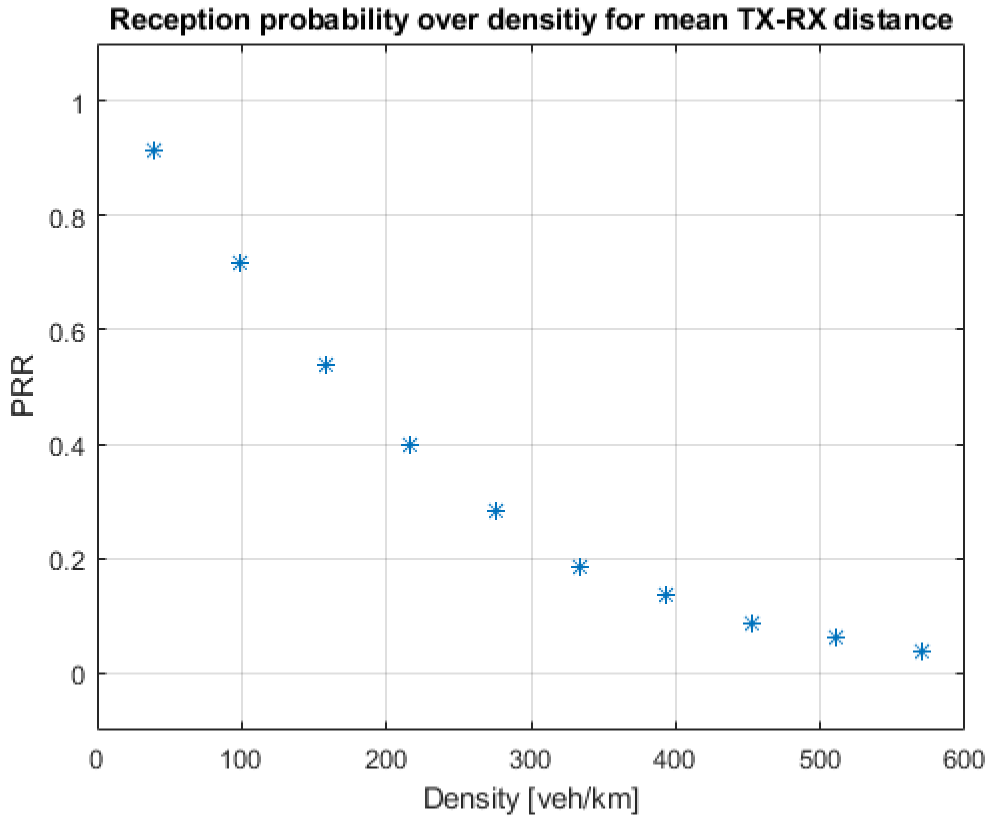
Figure 3.9. Consists in the linear depot



decrease like an exponential.

A second observation is that even in the best possible condition the OOC approach reach at maximum 90% of reception probability due to collision and half duplex impairment.

Figure 3.10. PRR over density



Comparing Figure 3.10 with Figure 3.5, we can see that while using semi-persistent scheduler the capacity is high enough to handle all users and so is independent by density, using OOC codes, collisions depends from how many users are in the system, so it is dependent from density. As said before, comparing the two plots we can see OOC PPR is lower for every density configuration, except when in the depot two users are further than 400 m.

To better understand the conversion among 2D density of depot scenario and 1D linear scenario, the Table 3.3 is used.

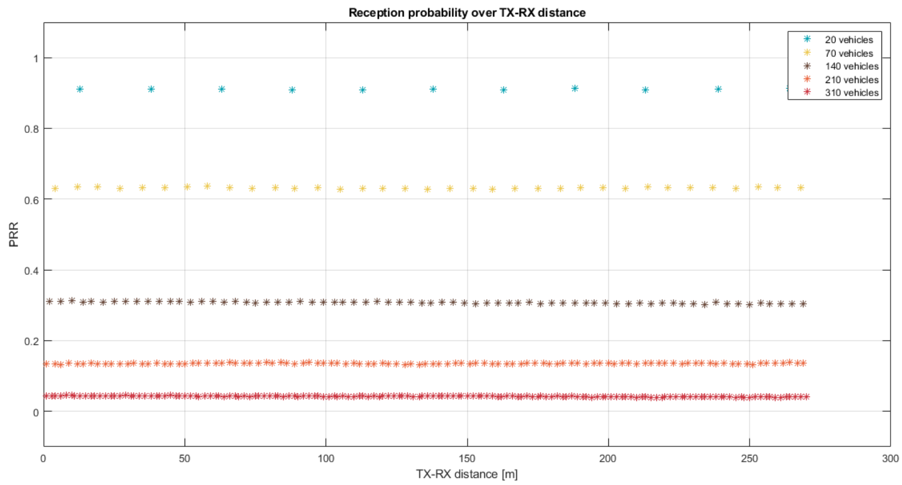
OOC scheduling over distance In Figure 3.11 we can notice that performance does not change in function of distance, because the physical layer is not implemented in the code, so the behaviour of MAC layer is just influenced by number of users in the system. So practically, the results shown are the maximum performances the system can reach in optimal condition, i.e. at very low distance.

In comparison with semi-persistent scheduler approach we see that performances

Table 3.3. 2D-1D table conversion

2D density[veh/hm^2]	vehicles in the system	1D density[veh/km]
87	20	40
130	70	130
180	140	260
250	210	390
500	310	570

Figure 3.11. PRR over distance



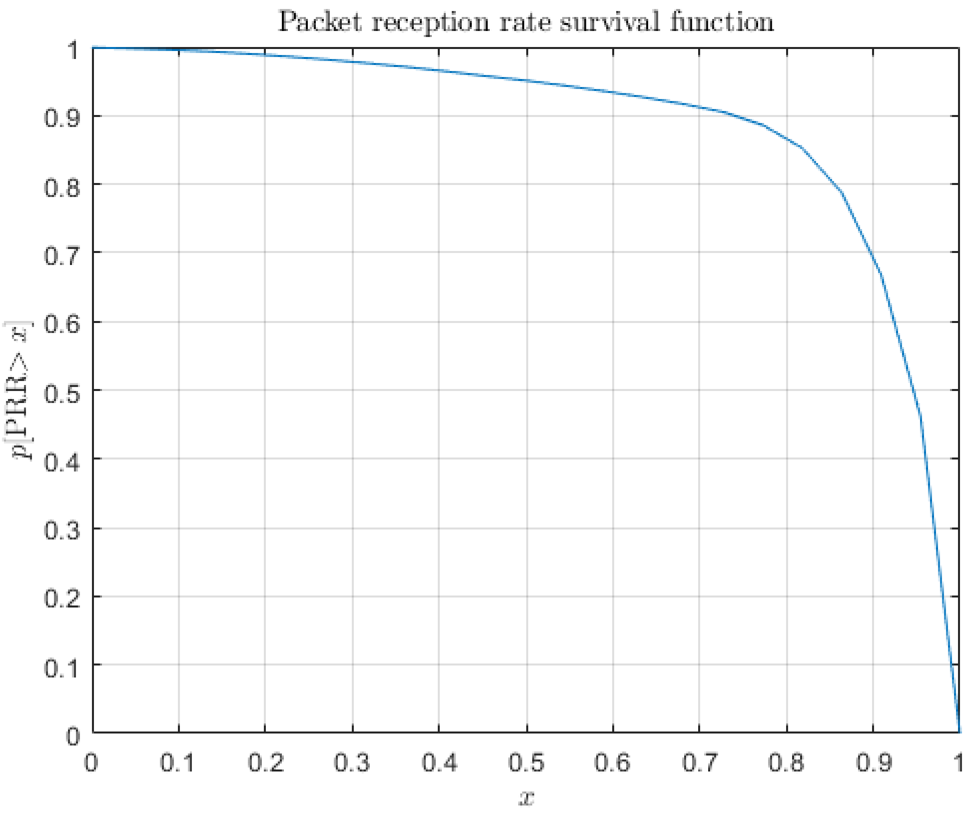
are worse: best PRR is around 90%, much worse that respective PRR in same condition with SPS, where PRR is around 99%.

OOC scheduling distribution probability In Figure 3.12 it is shown the survival function of received packets, or in other words, it is shown the reliability of a packet to be received. In particular we have shown a density of 40 veh/km, that corresponds to 20 consists in the linear depot. If we look the reliability, we can see that at 70% the PRR would be greater then 90%, then the probability decrease quite fast.

From this plot we can state that due to many collisions or half duplex impairments, the reliability is not suitable for the application.

OOC scheduling over different fixed packet size We have analysed how the system behaves for packets whose size remain fix. In Figure 3.13 are plotted curves

Figure 3.12. Reliability for density at $70veh/km$



at different densities, depending on packet size. We can see that the PRR decrease exponentially, increasing with packet size, but for small packets the curve tends to be almost linear.

The best possible performance is when we have low packet size and few consists in the depot, reaching a PRR around 99%.

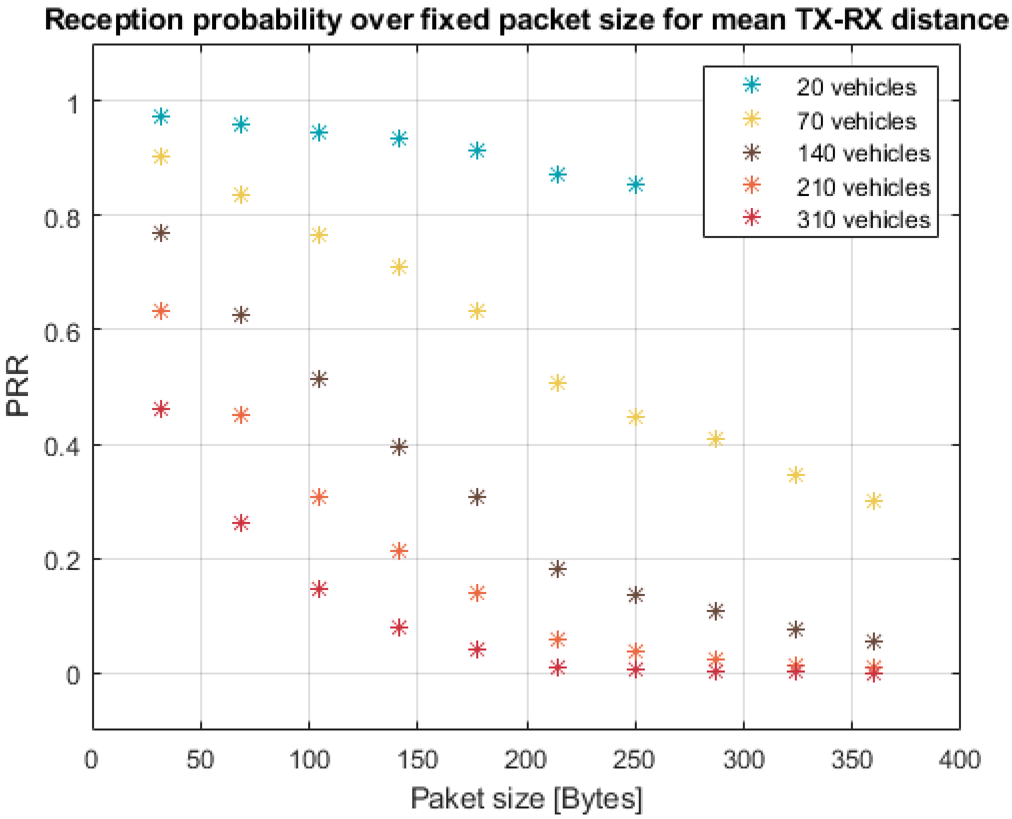
Comparing with the corresponding plot using semi-persistent scheduler, we can see that OOC approach is worse

OOC scheduling over variable packet size In Figure 3.14 is shown the behaviour of the system, when packets are not all the same, but they have different sizes, distributed as a gaussian, with mean equal to 200 and standard deviation equal to 80. This means that 95% of packets have size between 40 and 360 bytes.

These values are a lower than the corresponding plots of semi-persistent scheduler, but in this case the mean value is much closer to system packet size: 179 bytes.

We can immediately observe that PRR does not depend from distance, but it

Figure 3.13. PRR over different packet size



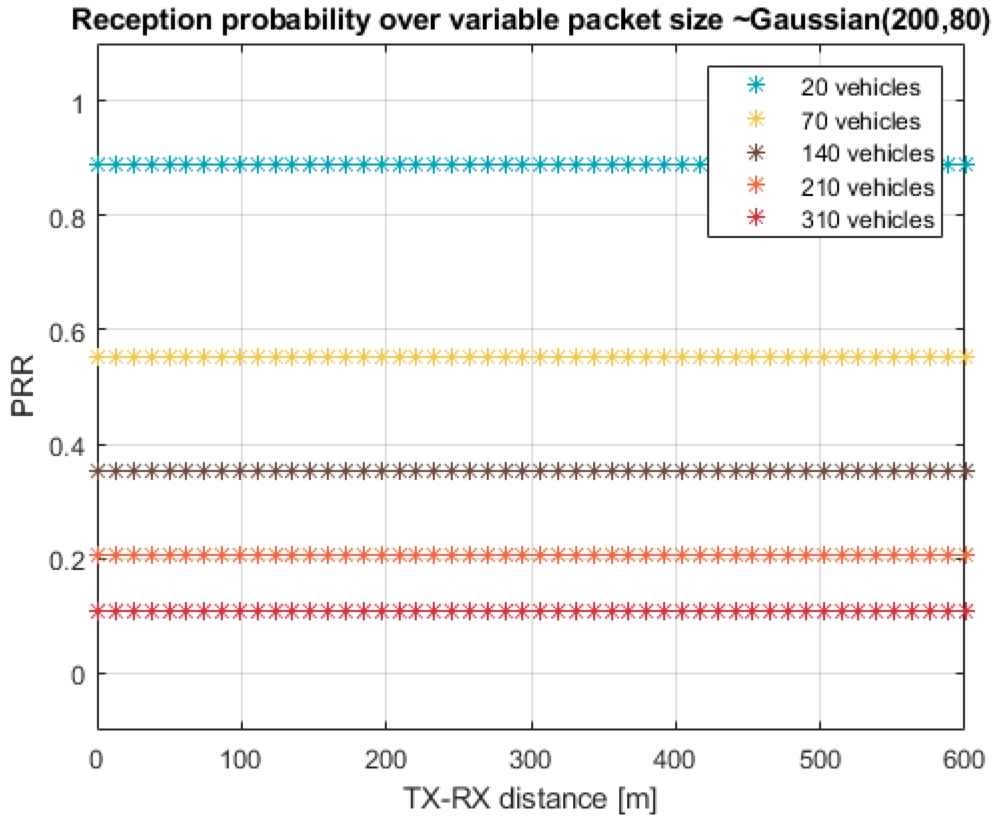
depends from density. Again, we can see that best performances are reach for small number of vehicles and the PRR is around 90%, still lower confronting to semi-persistent scheduling approach.

OOC scheduling over different modulations One experiment has done just in OOC scenario and results are shown in Figure 3.15. Ideally we want to change the modulation and coding scheme (mcs) different from 7 to see the difference in the system. According to the provided code, that just analyse the MAC layer, this modification consists just into a modification of bits per resource elements, or in other words, modification of the transmitted symbols modulation.

Looking at the PRR in function of density, we can see an exponential decreasing, exactly how was with Figure 3.10, where the used modulation was QPSK. But if we use higher modulations, PRR increase from 90% to 99% for small amount of consists and still remains above 80% for densities around 200 veh/km.

Unfortunately we don't have the corresponding results for SPS, but we can imagine that the same improvements are reasonable in the SPS approach. This

Figure 3.14. PRR over gaussian distributed packet size



consideration is quite important because if we would choose a linear topology, preferring it to a mesh topology, the distance among antennas would be very low, this would mean good transmission condition and so a better modulation is feasible.

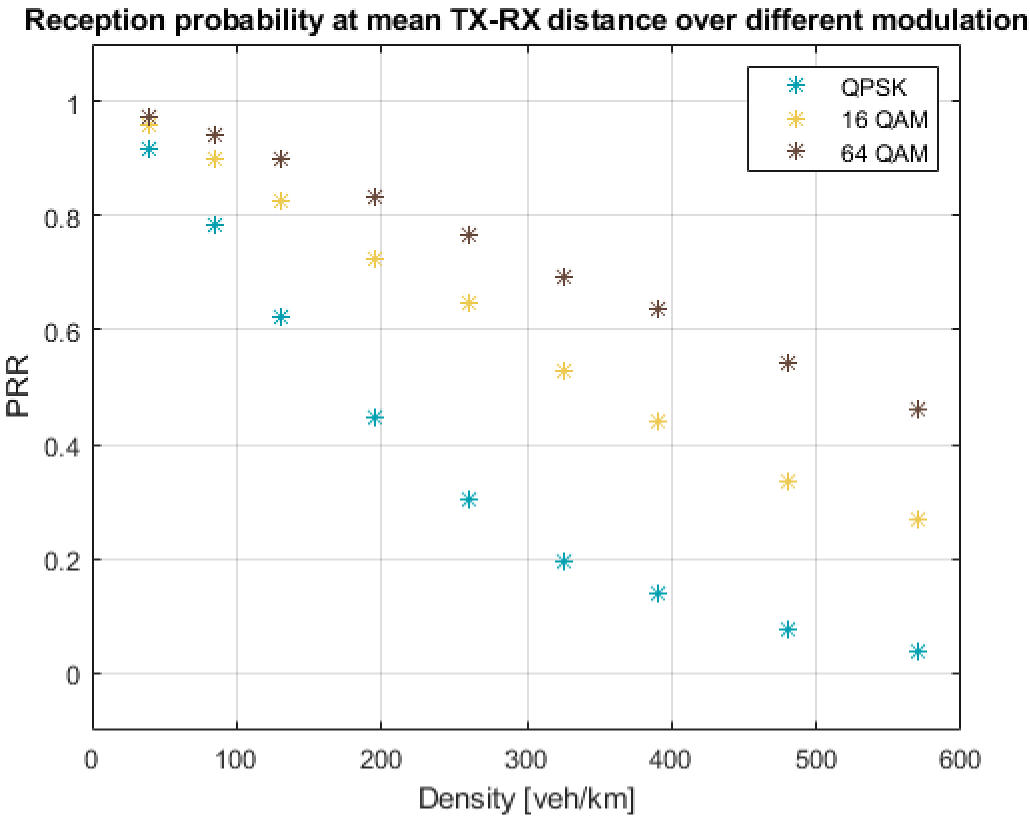
3.3.3 Comparison between semi-persistent scheduler and optical orthogonal codes scheduler

Confronting the plots among each others is evident that semi-persistent scheduler performs better. We have analysed both approaches for behaviour related to distance and density and looking at best conditions SPS is better.

Regarding reliability of transmission on one hand the system touches peaks of 99.9% with good probability, reasonably reachable under a linear topology, while on the other hand the probability to have a reliability of 90% is pretty low.

Finally, looking at packet size, both fixed or variable, the semi-persistent scheduler gives better reception probability.

Figure 3.15. PRR over different modulation



Chapter 4

Conclusion and future work

After having analysed the behaviour of the system and having appreciated the comparison between the two proposed algorithms, in this final chapter we draw conclusions about our experiments and we describe what will experiment next, to better research on this field, to reach our objectives.

4.1 Conclusion

We have analysed many system parameters in order to look at some performances, but for both tested schedulers we are still quite far from requirements for time sensitive networks. Nevertheless, there are some important results that we can remember.

The most important one is the 0.999 reliability in a transmission at 10 meters. This results assure a good condition transmission per hop in a linear topology. Linear topology would imply more packets to send and multi-hop problem, but in case these problems would find solution, per hop conditions are good.

The second observation that we can make is the obvious superiority of semi-persistent scheduler with respect to optical orthogonal codes. This can be explained because OOC assign slots to users without considering the users already in the channel, while semi-persistent approach sense the channel before choosing the transmitting slots.

Finally we need to observe that when transmission conditions are good we could improve performances increasing the modulation, and even considering a variable packet size could be beneficial for the system, because even if the behaviour in mean remain the same, it is better for lower distances and lower densities.

4.2 Future works

This thesis analyses performaces of OOC algorithm simulated in MATLAB. The next step would be looking at the same experiments using an STDMA scheduler in MATLAB, to see if performances increase in respect to semi-persisten scheduler. If so, would be better to have the same scheduler in NS3 environment and simulate the scenario in a full stack implementation, comparing results with the corresponding using semi-persistent scheduler. After the NS3 simulation, the next interesting step would be implementing the STDMA scheduler in Open Air Interface (OAI) and emulate the scenario first in the emulator environment, then test the scheduler deploying the code directly in real world.

Finally, in March 2020 the 3GPP release 16 would be frozen and physical layer would be specified, as well as the scheduler: an interesting comparison would be applying STDMA or semi-persistent scheduler on 5G physical layer and comparing it with the standardized scheduler.

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