I. Thesis Context

Nowadays, vehicular networks form a large and important research field, attracting automotive and telecommunication industries. The Cellular Vehicle-to-Everything (C-V2X) is an emerging technology for vehicular networks in which resource allocation mechanisms play a crucial role in its overall performance. In this regard, the resource allocation in C-V2X has drawn the attention of the research community, in the last few years. Besides, vehicular communications impose more challenges to the resource allocation problem due to constant changes in the network topology caused by the high mobility. Therefore, resource allocation in C-V2X is a key aspect to improve its performance.

One of the challenges of resource allocation in C-V2X is to efficiently allocate resources to vehicles to meet the requirements of different V2X applications. Since the first goal of vehicular networks is to ensure road safety service, we are interested in the initial contribution to safety-related applications. For this reason, we propose a new efficient resource allocation algorithm in mode 3 of LTE-V2X for safety traffic, the MIRD algorithm. The main goal of MIRD algorithm is to improve the reliability of safety V2V communications by efficiently allocating radio resources to vehicles using a clustering approach.

The second part of our thesis deals with resource allocation considering the 5G-V2X technology. One of the main differences between LTE-V2X and 5G-V2X is the flexibility of the NR frame structure of 5G thanks to the introduction of the numerology concept, which was not previously considered in LTE-V2X. Therefore, before starting the allocation of radio resources, it is necessary to choose the appropriate numerology for each V2X scenario. To do so, we first studied the impact of 5G numerologies on the performance of V2X applications.

Still in the 5G-V2X resource allocation context, we then propose a new resource allocation algorithm that considers simultaneously the safety and non-safety applications, the PSRA-MN algorithm. As the safety-related applications are the most critical applications in vehicular networks, the application of a priority policy in favour of the safety applications is a necessary step. The main idea of the PSRA-MN algorithm is to ensure the necessary resources for safety vehicles by applying a priority mechanism in favour of safety traffic. Next, the remaining resources after safety allocation are then allocated to the non-safety vehicles by solving an integer linear optimization problem that aims to maximize the average satisfaction rate of non-safety vehicles.

II. State-of-Art

With respect to the state-of-the-art on resource allocation in C-V2X, we note that the resource allocation algorithms proposed in the literature do not take into account the QoS requirements and categorization of different V2X applications. There is an attempt in this direction in [1], where Allouch *et al.* propose a new algorithm for mode 3, named Priority and guarantEed-bAsed Resource aLlocation (PEARL) algorithm. In the PEARL algorithm, authors classify the V2X traffic in two types: safety traffic and non-safety traffic. In this work, the authors aim to guarantee the minimum of resources to the basic safety traffic. For that, the algorithm reserves a guaranteed group of resources for the safety traffic, which is used in case of high traffic density. The guarantee of those resources aims to ensure that the vehicles have always the needed resources to transmit their basic safety messages.

Considering the choice of the appropriate numerology for each V2X scenario, we note that it is not widely investigated in the literature. To the best of our knowledge, the only research work that makes an attempt in this direction is the one presented in [2], where the authors study the impact of 5G numerologies on V2X communication performance. However, the limitation of this work is that the authors have only focused on the physical level performance evaluation and neglected the impact of these numerologies on the application level system performance. In addition, the authors do not consider a wide range of use cases for the channel conditions, which makes this study is not very exhaustive.

III. Scientific Results

A. *Contribution 1: Proposition of MIRD Algorithm for LTE-V2V Communications*

In this contriution, we propose a new algorithm for resource allocation in LTE V2X, where we are only interested in the safety-related traffic. The proposed resource allocation algorithm, which we call the Maximum Inter-Centroids Reuse Distance (MIRD) algorithm, is based on the clustering technique.

Figure 1(a) shows the variation of the PRR in function of the distance between transmitter T_x and receiver R_x for MIRD algorithm compared to the reference algorithm $Algo_{ref}$. The difference between MIRD and $Algo_{ref}$ is very clear in the figure for the distances higher than 100 m. For example, for the same distance of 150 m, the PRR of MIRD is about 92%, while the PRRs of $Algo_{ref}$ is about 81%.

Figure 1(b) illustrates the ABR of MIRD compared to the reference algorithm. As shown in the figure, MIRD presents an ABR equal to 0% thanks to the resource reuse approach, while the ABR of $Algo_{ref}$ is not null. This is explained by the blocking of transmitters when there are no resource available.

Figure 1(c) shows the values of the resource reuse rate for three traffic scenarios with a fixed number of resources $N = 40$ resources. As shown in the figure, the resource reuse rate increases with the increase of the number of vehicles. For $M = 80$ vehicles, the resource reuse rate is $T = 50\%$ which increases also the resource allocation capacity.

Based on the obtained results, we demonstrate that MIRD algorithm achieves better performance by increasing the reliability of safety V2V communications.

B. Contribution 2: 5G Numerologies and their Impact on V2X communications

The 5G numerologies are an enabler to meet the requirements of a wide range of 5G services. Indeed, V2X communication encompasses a variety of applications with different requirements. Therefore, the choice of the appropriate numerology for each V2X scenario is of particular importance. To this end, in this contribution we present a comprehensive study of the impact of 5G numerologies on the performance of V2X applications

Our study can be divided into two parts. In the first part, we have studied the impact of the 5G numerologies on the performance of V2X applications by considering the throughput and latency parameters, while in the second part we are interested in the impact at the physical layer by considering the BER (Bit Error Rate) parameter.

1) Application layer performance evaluation: Figures 2(a) and 2(b) show the average latency and average throughput for safety and video streaming applications, respectively. When we vary the numerology index from 0 to 3, we find that the average throughput increases with the increase of the numerology index, unlike the latency, which decreases as the numerology index increases.

2) Physical layer performance evaluation: Figure 3(a) show the BER as a function of vehicle speed, considering delay spread value of 37 ns for the rural scenario. As can be seen in Figure 3(a), the BER increases with the increase in vehicle speed. This can be explained by the ICI (Inter-Carrier Interference) caused by the Doppler effect due to vehicle mobility. However, we note that for the same vehicle speed, the BER decreases as the numerology increases. This behavior can be explained by the fact that as the numerology increases, the sub-carrier spacing is increased and the system is then less affected by the ICI phenomenon. For that, the lower numerologies are more affected by the ICI than the higher numerologies due to their lower sub-carrier spacing values.

Figure 3(b) show the variation of the BER as a function of vehicle speed considering the delay spread value of 363 ns for the urban scenario.

Looking at the curves of numerologies 2 and 3, we notice that the BER values are higher for a delay spread of 363 ns than for a delay spread of 37 ns. Moreover, we find that the BER is higher with numerology 3 when compared to numerology 2. Thus, we conclude that the system performance decreases significantly when using higher numerologies as the delay spread of the channel increases. Indeed, the system performance is more susceptible to the ISI (Inter-Symbol Interference) problem when using the higher numerologies due to their shorter cyclic prefix. For this reason, we note that in urban scenarios and with higher delay spread values, it is not recommended to use the higher numerologies.

Finally, we conclude that the choice of the appropriate numerology is a trade-off between the stringent requirements of V2X applications, the ICI problem, and the ISI problem.

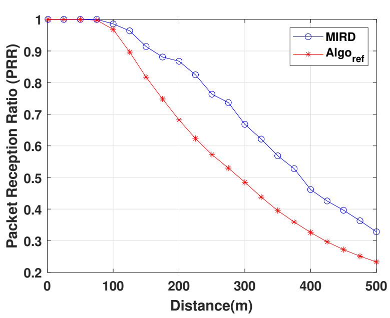
C. Contribution 3: Proposition of PSRA-MN Algorithm for 5G-V2X Communications

In this contribution, we propose a new Priority and Satisfaction-based Resource Allocation algorithm with Mixed Numerology for 5G V2X communications (PSRA-MN). In PSRA-MN, we apply a priority policy in favour of the safety traffic, since the latter is the most time-constrained V2X traffic type. Then, the remaining resources after ensuring the demands of safety traffic are optimally scheduled for the non-safety traffic. The PSRA-MN algorithm is executed in a mixed numerology scenario, in which different 5G numerologies are multiplexed in the time domain. The PSRA- MN scheduling scheme is validated through simulations conducted using the Simu5G simulator.

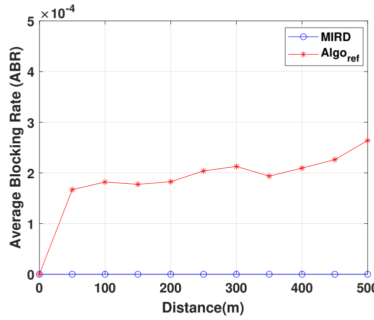
Figure 4 shows the average allocation rate for safety traffic in function of the number of RBs, for the PSRA-MN algorithm compared to the Max-C/I algorithm. The AAR increases when the number of RBs increases for both algorithms. The difference between PSRA-MN and Max-C/I is very clear in the figure for the lower number of RBs. As can be seen from Figure 4, for a fixed number of RBs, the AAR for safety traffic is higher for the PSRA-MN than for the Max-C/I algorithm. For example, with 50 RBs, the AAR for PSRA-MN exceeds 40%, whereas the AAR for Max-C/I in this case does not reach 30%.

Figure 5 shows the average satisfaction rate for non-safety traffic as a function of the number of RBs for the PSRA-MN algorithm compared to the Max-C/I algorithm. The ASR increases as the number of RBs increases. As can be seen in this figure, for a fixed number of RBs, the ASR is higher for PSRA-MN than for Max-C/I. For example, with 100 RBs, the ASR of PSRA-MN exceeds 90%, while that of Max-C/I does not reach 30%.

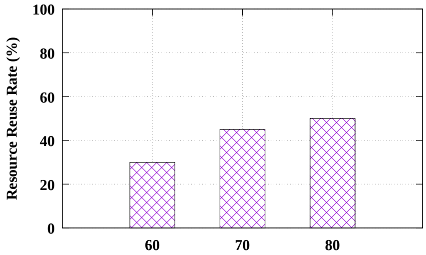
Figure 6 shows the average delay for safety traffic for our algorithm with fixed and flexible numerology, which corresponds in the figure to PSRA and PSRA-MN, respectively, compared to Max-C/I. As can be



(a) The Packet Reception Ratio (PRR)

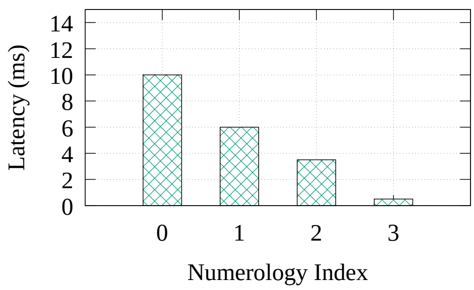


(b) The Average Blocking Rate (ABR)

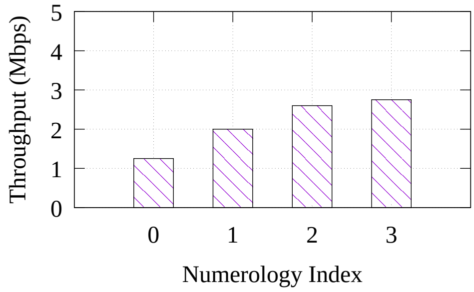


(c) The Resource Reuse Rate (λ) for MIRD in 3 traffic scenarios

Figure 1: The Packet Reception Ratio (PRR), the Average Blocking Rate (ABR) and the Resource Reuse Rate (λ) for MIRD compared to $Algo_{ref}$ in an urban scenario of Bologna

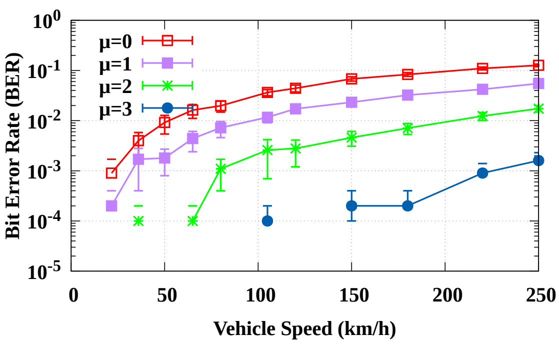


(a) Average Latency as a function of numerology for Safety V2V application

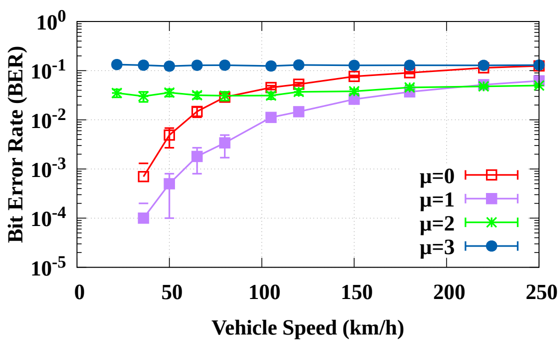


(b) Average Throughput as a function of numerology for UDPVideoStream application

Figure 2: Average Latency and Average Throughput as a function of numerology



(a) BER with delay spread = 37 ns



(b) BER with delay spread = 363 ns

Figure 3: BER as a function of vehicle speed varying numerology index (μ)

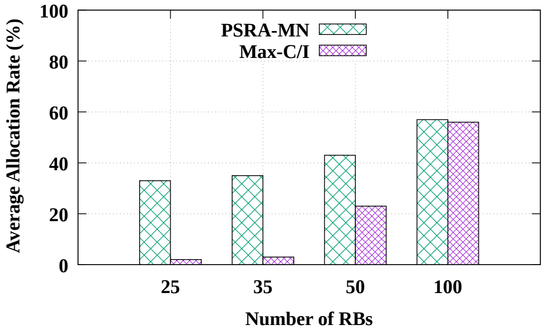


Figure 4: The Average Allocation Rate (AAR) for safety traffic

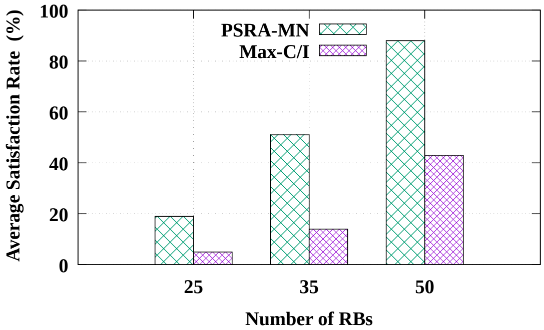


Figure 5: The Average Satisfaction Rate (ASR) for non-safety traffic

seen in this figure, the average delay of both PSRA and PSRA-MN is lower than that of the Max-C/I algorithm. The average delay of the PSRA algorithm is about 16 ms and that of PSRA-MN is about 6 ms, while the average delay of Max-C/I algorithm exceeds 20 ms. In fact, there are two reasons for this result. First, unlike the PSRA algorithm, in the Max-C/I algorithm a safety vehicle must sometimes wait until another non-safety vehicle is scheduled, which increases the overall safety message delay for Max C/I. Second, the use of the TDM multiplexing approach allows the use of different numerologies. However, when a high numerology index is used, the average delay decreases. For this reason, when mixed numerology is used in our scheduling scheme, PSRA-MN has the lower average delay value compared to PSRA and Max-C/I.

The obtained results show that PSRA-MN outperforms Max-C/I in terms of the average allocation rate, the average satisfaction rate, and the average delay.

IV. List of Publications

A. Journals

- Sehla Khabaz, Thi-Mai-Trang Nguyen, Guy Pujolle, and Pedro Velloso, "Resource Allocation Modes in C-V2X: From LTE-V2X to 5G-V2X," in IEEE Internet of Things Journal, vol. 9, no. 11, pp. 8291-8314, 1 June1, 2022, doi: 10.1109/JIOT.2022.3159591.

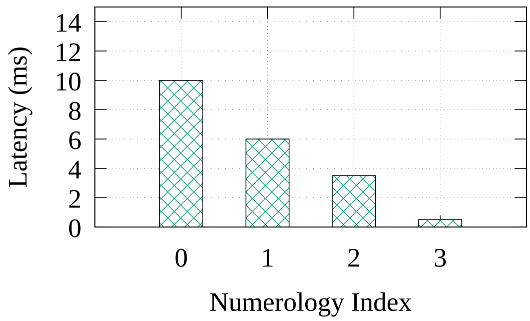


Figure 6: The Average end-to-end delay for safety traffic

B. Conferences

- Sehla Khabaz, Thi-Mai-Trang Nguyen, Guy Pujolle, and Pedro Velloso, "A New Clustering-based Radio Resource Allocation Scheme for C-V2X" 2021 Wireless Days (WD), 2021, pp. 1-8, doi: 10.1109/WD52248.2021.9508289.

- Sehla Khabaz, Kaouthar Ouali Boulila, Thi-Mai-Trang Nguyen, Guy Pujolle, Moustapha El-Aoun, and Pedro Velloso, "A Comprehensive Study of the Impact of 5G Numerologies on V2X Communications", 2022 13th International Conference on Network of the Future (NoF), October 05 - 07, Ghent (Belgium).

- Sehla Khabaz, Kaouther Ouali Boulila, Thi-Mai-Trang Nguyen, Guy Pujolle, Moustapha El-Aoun, and Pedro Velloso, " A New Priority and Satisfaction-based Resource Allocation Algorithm with Mixed Numerology for 5G-V2X communications ", 2022 14th IFIP Wireless and Mobile Networking Conference (IFIP WMNC), October 17 - 19, Sousse (Tunisia).

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[1] M. Allouch, S. Kallel, A. Soua, and S. Tohme, "PEARL: A Novel Priority and Guaranteed-based Resource Allocation Approach for V2V Communications in LTE-V Mode 3," in *2020 8th International Conference on Wireless Networks and Mobile Communications (WINCOM)*, pp. 1–6, IEEE, 2020.

[2] J. F. de Valgas, D. Martín-Sacristán, and J. Monserrat, "5G New Radio Numerologies and their Impact on V2X Communications," *Waves, Univesitat Politecnica de Valencia*, pp. 15–22, 2018.