EVALUATING B2X WIRELESS COMMUNICATION WITH A TRAFFIC SIMULATOR IN URBAN SCENARIOS

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1 ABSTRACT

Bicycles are key solutions that promote a healthy lifestyle as cities place a greater emphasis on sustainable mobility. Simultaneously, the incorporation of Internet of Things (IoT) technology, including bicycle-to-everything communication (B2X) systems, into bicycles holds significant potential to revolutionize urban safety and traffic efficiency. Bluetooth low energy (BLE) could enable communication among bicycles, but the distinct mobility patterns of bicycles could be a challenge to BLE communications, particularly in crowded cities. This work uses a simulation-based analysis to explore these issues. We suggest an approach that combines SUMO a traffic simulator with MATLAB's Bluetooth Toolbox to model BLE communication. We intend to examine the effects on BLE network performance, including packet loss rate and communication latency, by simulating scenarios with different bicycle densities.

Additional Key Words and Phrases: B2X, traffic simulator, BLE, density.

2 INTRODUCTION

Nowadays there has been an increase in environmental awareness and a constant search for sustainable alternatives, in this context governments and cities are immersed in a process of modifying their mobility policies. In this situation, bicycles emerge as a promising solution to reduce pollution and energy consumption, while also promoting an active and healthy lifestyle in cities. This shift towards sustainable mobility has led to the encouragement of a series of initiatives aimed at promoting the use of bicycles as a preferred means of transport in urban areas as can be seen in the European Declaration of Cycling [1] where is stated: “We aim to unleash the full potential of cycling in the EU”.

With this increase in the number of bicycles on the road, mobility, and road safety are challenges that need to be addressed. With the increase in the number of Internet of Things (IoT) devices playing a central role in our daily lives, recently there has been an increase in the development and adoption of IoT devices applied to bicycles from tracking and tracing systems to active safety devices such as smart lights and proximity sensors, which are radically transforming the experience of cycling in urban environments. These advancements improve cyclist safety and efficiency and provide new opportunities for traffic management and urban planning as stated by Heather Twaddle and colleagues[2]. In this attempt to improve city safety and traffic efficiency, the idea of incorporating B2X (Bicycle-to-Everything) communication systems into bicycles is proposed, taking as a reference the already existing V2X (Car-to-Everything) communication model. An infinite range of possibilities are opened up by this vision, which aims to establish an integral communication network between all the elements of the city. BLE (Bluetooth Low Energy) is a major wireless communication technology in the B2X communication space. It is extensively used in mobile devices and has a low energy consumption, making it perfect for compact devices. However, there are unique wireless communications issues because of the high bicycle density in metropolitan environments. It becomes necessary to look at how B2X communications are affected by circumstances that might affect transmission capacity due to BLE device congestion in highly populated metropolitan areas. The creation of realistic traffic simulators that mimic real-world situations is necessary in order to tackle this problem. With the help of these simulations, we will be able to assess how bicycle mobility affects BLE communications by considering factors such as bicycle densities.

Although studies have been carried out on V2X communications, there is a lack of studies that have yet been made that consider the unique characteristics of bicycle mobility and its effects on B2X communications. Due to the generalized use of IoT devices that implement BLE technologies and the expected increase in the use of bicycles as a means of transport, it is necessary to study the future problems that could arise in urban environments caused by the unique density patterns of bikes. According to the study of L. Huang and J. Wu [3], cyclists in urban areas, can form clusters, change lanes, turn at intersections, dismount and walk, perform erratic movements to avoid obstacles, use different types of roads, and quickly accelerate or decelerate. These characteristics in the mobility patterns of bicycles could affect BLE communications since the quick changes in location or speed as well as the high density could cause problems with loss of packets or communication loss between devices, either because the distance between them exceeds the range of the BLE or interfere with the signal.

To perform this study it is necessary to have a realistic bicycle traffic simulation as stated by Heather Twaddle, Tobias Schendzielorz, and Oliver Fakler in their review of the existing modeling behaviors of bicycles [2], the behavior of bicyclists is considerably different from those of motorized vehicles and therefore it is necessary to use specific simulation models for the study of bicycles in urban environments to obtain reliable results.

The problem statement will lead to the following research question:

How do the unique mobility patterns of bikes affect BLE communications?

This can be answered with the following sub-questions:

(1) How to realistically represent bicycle mobility in a traffic simulator using SUMO?

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(2) How are BLE communications affected by a high and a low density of bicycles?

This research involves multiple steps. First, a literature review will be done to obtain more information on the realistic simulation of bicycles in traffic simulators. This information will be used to implement a realistic simulation of a bicycle in SUMO (Simulation of Urban Mobility) [4], a traffic simulation tool widely used to model the movement of vehicles and pedestrians in urban environments. We will use TraCI4Matlab [5], an implementation of the TraCI (Traffic Control Interface) protocol that allows the interaction of SUMO with MATLAB. MATLAB [6], is a platform of numeric calculus and programmation, that will be used to interpret the information obtained by SUMO and provide instructions to the bicycles on how they should behave in the simulation.

Second to address the study on how bicycle density affects BLE communications, a simulation will be carried out using two different scenarios: the first one will be a scenario with a high density of bikes and the second one will be a scenario with a low density of bicycles. These scenarios will be created using SUMO and the information obtained in the previous step to obtain realistic simulations. To interact with SUMO and analyze the simulation results, TraCI4Matlab, an interface between SUMO and MATLAB, will be used. Once the high and low bicycle density scenarios have been configured in SUMO, a BLE communication network will be simulated using MATLAB's Bluetooth Toolbox [6]. This tool provides functionalities to model and simulate Bluetooth devices that are incorporated into bicycles to allow bicycle communication, which will allow studying how BLE communications are affected depending on the density of bicycles in the environment.

During the simulation, data such as packet loss rate, and communication latency will be collected to be analyzed using statistical techniques and visualization tools in MATLAB to assess the impact of bike density on BLE network performance.

3 RELATED WORK

To gather related literature to the research domain Scopus, Google Scholar, and IEEE were used. Search terms such as "bicycle", "bicycle to everything communication", "simulation" and "Bluetooth low energy" were used in the search.

Most of the findings were in the field of bicycle simulation [2,7,8,9]. Various simulators were identified, such as SUMO (an open-source traffic simulator), MATSim (a multi-agent transport simulation platform), VISSIM (a commercial traffic simulator by PTV Group), AIMSUN (another commercial simulator used in urban planning), and SimMobility (a MIT-developed platform for different scales of simulation). For our research we selected SUMO. As it was pointed out in the Sumo conference [10] there is a need for a model that can imitate the unique characteristics of the traffic flow behaviors of bicycles and the need to allow an easier implementation of force models and physics-based models. As stated by Ahmet-Sedar et all in [11] the default bicycle simulation of SUMO is not realistic. Here are some of the suggestions to improve the simulation of bicycles in SUMO made during the sumo conference. Firstly, it was suggested to enable the parameter "—device.rerouting.bike-speeds" that provides a separate method to calculate the average speed of bikes, but it comes at the cost of a slower simulation and more computing cycles since by default the simulation of bikes in SUMO uses the same routing algorithms as vehicles. It was also explained that SUMO allows to set bikes as a pedestrian to simulate situations where cyclists dismount their bikes as it could be the case of crossing a road, accessing public transport, or going inside a building and it also allows the setting of areas where bikes can be left and picked up. It is stated that it is necessary to improve the sub-line selection, car-following, and subline changing as stated in the SUMO conference of the state of bicycle simulation since bicycles are more manurable, since bikes are easier to steer accelerate, and decelerate.

However, it was difficult to find any information about the effects of bicycle mobility in BLE communications, some information was found about the study of BLE communications in V2X communications on different traffic scenarios[12]. And in the field of B2X communication studies a paper about ZigBee-based wireless communications was found [13]. This lack of papers is due to most of the studies on the field being made in V2X communications.

4 SIMULATION ENVIRONMENTS

The traffic simulator of choice was SUMO for several reasons. Although it originally modeled only four-wheeled vehicles, it has been adding functionalities that allow the modeling of heterogeneous traffic and in particular bicycles. This capability is essential for our study, which focuses on bicycle traffic. Also decisive in its choice was the ease of communication with other tools through TraCI allowing the control of the behavior of all simulated objects, in our case essential to interact in real-time simulation with the network simulation. But no less important is the fact that it is a microscopic traffic simulator, i.e. it is based on the individual emulation of the movement of each vehicle participating in the scenario, so SUMO is able to adopt a different movement to each vehicle in the scenario, thus making an environment closer to reality. This will allow us to obtain specific parameters of each vehicle, thus including microscopic parameters as well as macroscopic parameters of the simulation. It also allows modeling complex traffic interactions, such as lane changes, traffic lights, and bottlenecks, and the possibility of modifying a large number of parameters of our model. Its graphical user interface (GUI) is customizable and easy to use allowing us to view the simulation in real time. In addition to this interface, it includes a set of support tools that facilitate tasks such as route generation and map import. Of course, there are other features that make it an interesting software such as the fact that it is Open Source and its large community of users and developers.

Matlab has been chosen for the simulation of the Bluetooth LE network. Matlab stands out for its wide range of toolboxes, and among them, Bluetooth Toolbox is one of the most relevant for this project, as it provides a complete set of tools to design, simulate, and verify a complete set of tools for the design, simulation, and verification of Bluetooth communication systems, including Bluetooth Low Energy (LE). Specific capabilities of Bluetooth Toolbox include the ability to model all layers of the Bluetooth LE protocol, signal generation, and decoding, simulation of interference and channel effects such as fading and delay, performance analysis by providing metrics and tools to evaluate communication performance such as bit error rate (BER), latency and throughput. Another point that has been fundamental in its choice is Matlab's ability to interoperate with other tools and platforms. In this project, Matlab can be easily integrated with SUMO using TraCI4Matlab to combine traffic data with communication simulations and keep both simulations synchronized, as they will exchange information during the runtime of the simulations in both directions. But Matlab has not only been used for simulation but also for the analysis and visualization of the data obtained thanks to its powerful tools. This is essential to facilitate the interpretation of results and the clear presentation of conclusions. Finally, it is in constant development and something that has also been taken into account is that it is a software widely used in universities and research and development centers with a large community of users and an extensive resource base, including documentation, tutorials, and practical examples.

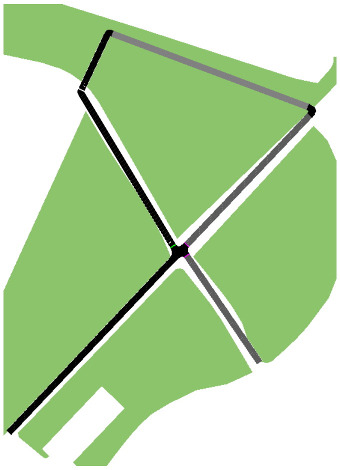

Fig. 1. SUMO simulation map

5 MEASUREMENT ENVIRONMENT

Two scenarios have been created in SUMO to study the effects of density in BLE communications. Firstly, a scenario to study the effects of the high density of bicycles in BLE communications. This scenario consists of a road layout that can be seen in Figure 1, the roads have one line with a width of 3m and a speed limit of 30km/h, to create an accumulation of bicycles there is a traffic light in the intersection located in the middle of the flow that the bicycles are going to follow that is on green during 1 second on yellow during 1 second and on red during 20 seconds. A flow of bikes from junction to junction that goes through the road in black in Figure 1, the flow has a random starting lane a random departure position, and a random departure speed with a number of 3600 bicycles that appear following a Poisson distribution of 0.5 insertions per second. This Poisson distribution means that bikes are inserted at exponentially distributed time intervals, resulting in an expected rate of 0.5 insertions per second. This ensures that the bicycles appear randomly over time rather than at fixed intervals, creating a more realistic simulation of bike traffic. To create a high-density flow the amount of traffic in this scenario has been scaled up by 20 using the SUMO option "−scale", which scales the flow by the selected amount. In this scenario, we simulate 38 bicycles over a period of 20 seconds traversing a distance of around 90 meters. Figure 2 displays the state at the end of the high-density simulation.

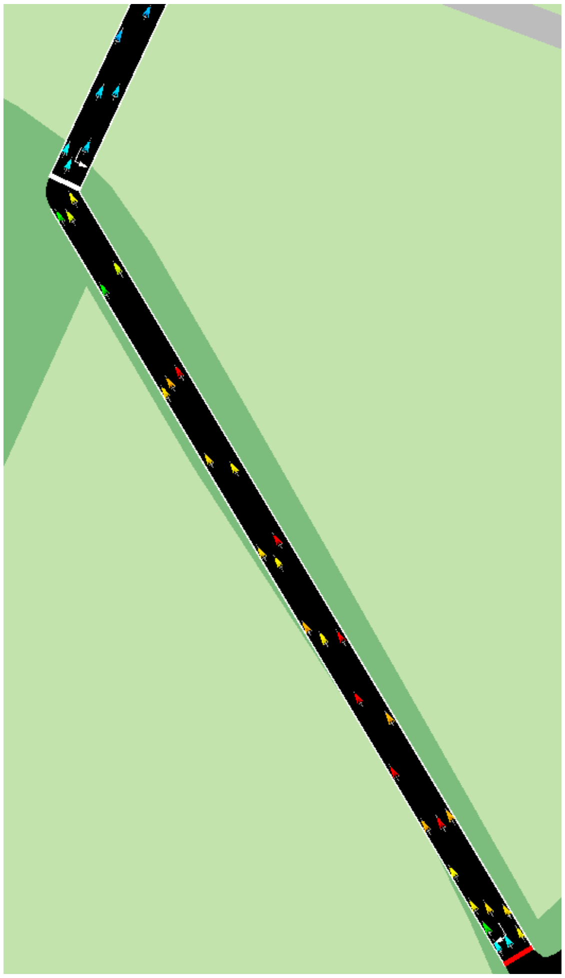

Fig. 2. High-density scenario

Secondly, a scenario to study the effects of low density of bicycles was created. The scenario has the same settings as the high-density scenario but the option "−scale" is set to one. This scenario will serve to contrast the data obtained from the high-density simulation and compare the results. In this scenario, we simulate 5 bicycles over a period of 20 seconds traversing a distance of around 90 meters. Figure 3 displays the state at the end of the high-density simulation.

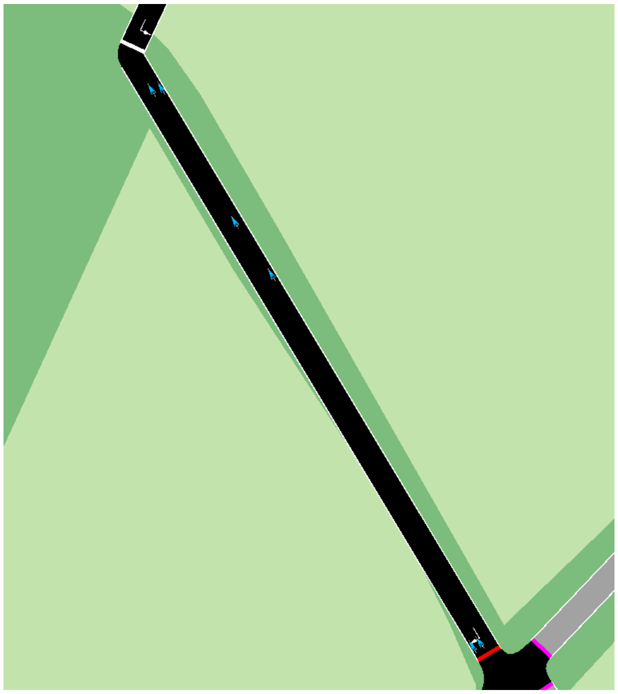

Fig. 3. Low-density scenario.

The configuration of the bicycles in the SUMO simulation can be seen in Table 1.

length	1.95 m
minGap	0.2 m
desiredMaxSeed	5.56 m/s
speedFactor	normc(1.00,0.10,0.20,2.00)
maxSpeed	30 km/s
width	0.64 m
height	0.1.23 m
accel	1.2 m/s^2
decel	1.5 m/s^2

Table 1. SUMO bicycle parameters

The length, height, and width are set based on the standard bicycle defined by [14]. The acceleration and deceleration are based on the values defined by [15]. The minimum gap is set based on the 0,25 safety distance described in the article [16]. The max speed is set to 30km/h based on the legal limit in the Netherlands on bicycle tracks in built-up areas [17]. When these changes are made the bicycles will appear as if they were of the vehicle type passenger Car. To solve this issue, it is necessary to edit the main SUMO file and add to "<routing>" the following parameter "<vType guiShape="bicycle"/>". Also, to allow more than one bicycle to circulate through the same line the main SUMO file was changed by adding to "<processing>" the line "<lateral-resolution value="2"/>".

The BLE communication configuration for the nodes can be seen in Table 2.

ReceiverRange	25 m
AdvertisingInterval	20e-3 s
ScanInterval	30e-3 s
DataRate	1 kb/s
PacketSize	15 B
OffTime	0.02*0.7 s
OnTime	0.02*0.3 s
TransmitterPower	20 dBm
TransmitterGain	0 dB
ReceiverGain	0 dB
RandomAdvertising	0 (false) boolean
InterferenceModeling	"overlapping-adjacent-channel"
Position	= bike position in SUMO

Table 2. BLE parameters

As the bicycles are moving in the SUMO simulator it is necessary to update the positions of the nodes in the network simulator accordingly. In our case the SUMO simulation progressed faster than the simulation of the nodes in the Bluetooth Toolbox, which caused them to be out of sync, since both movements must be perfectly synchronized and this functionality is not provided by Bluetooth Toolbox, we had to implement it. To synchronize the timers of both simulations firstly we let the SUMO simulation run for 0.1 seconds and is stopped, then the positions of the BLE nodes are updated to the position of its corresponding bicycles in the SUMO simulation. Secondly, the Bluetooth Toolbox simulation is run until the same time as the SUMO simulation. This process is repeated until the end of the simulation in intervals of 0.1 seconds.

Now we are going to describe some of the parameters that have been used during the simulation of the network. In the link layer, we measure the Cyclic Redundancy Check (CRC) to check if the packets are discarded because there are some bits that were altered during the transmission due to interference. In the physical layer, packet collisions are tracked to quantify the number of packets affected by simultaneous transmissions in the same channel, this parameter serves as a clear indicator of congestion. The amount of dropped packets is measured in the link layer, which are the packets that the physical layer has detected as non-valid specifically those that have failures in the decodification or have invalid access directions or invalid leghts. Throughput at the link layer is calculated based on the unique application bytes transmitted, measured in Kb/s, providing a clear metric of data transfer efficiency. Additionally, the average latency in the link layer, measured in seconds, indicates the time it takes for a packet to travel from source to destination, offering insight into communication delays.

To facilitate the interpretation of the results line graphs and heatmaps are used to display them. To allow the visualization of the progress of a selected parameter of the BLE nodes in real-time during the SUMO simulation a function has been implemented in Matlab that uses TraCI to change the colors of the bicycles in the

SUMO simulation based on the evolution of the selected parameter, the colors match the colors that will appear in the final heatmap for that parameter.

6 RESULTS

To effectively interpret the results presented in Figures 4, 5, and 6, it is important to understand the structure and content of the heatmaps since they provide a visual representation of the states related to packet handling during the simulation. The heatmaps illustrate the progression of the simulation on the x-axis (steps) and each individual bicycle on the y-axis. In each grid cell, the state of either the dropped packets (Figure 4), the CRC failed packets (Figure 5), or the packet collisions (Figure 6) for the BLE node, corresponding to that bicycle of the SUMO simulation, at that specific step is represented.

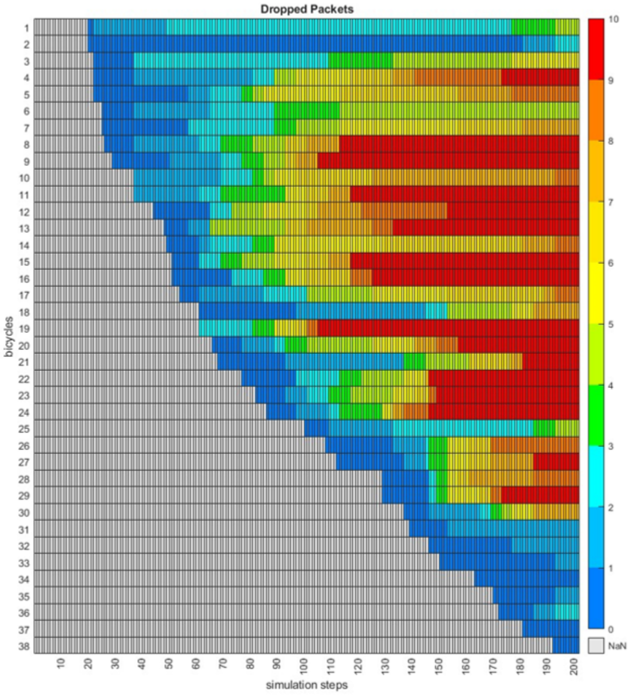

Fig. 4. Dropped packets heatmap.

In the results obtained at the high-density simulation, we observed that the throughput and latency weren't affected by the high density since their values remained the same during the simulation without a significant variation from the results obtained in the low-density simulation. This is due to the sender of a broadcast in BLE does not detect collisions and counts all transmitted data as part of the throughput. This explains why we observe similar throughput results in the simulations with different numbers of nodes since the throughput calculation will be based on the data sent and not on the data received correctly. In an environment with many devices, collisions can increase latency, since packets must be retransmitted. But in the case of broadcast there is no retransmission of packets. The recipient will not notice the missing packets, so it will not request a retransmission. Therefore packets that do not arrive are not counted in any way because the receiver is not even aware of their existence. On the other hand, packets that arrive without a problem will not be affected by collisions, so their latency will be the same as in a sparse environment.

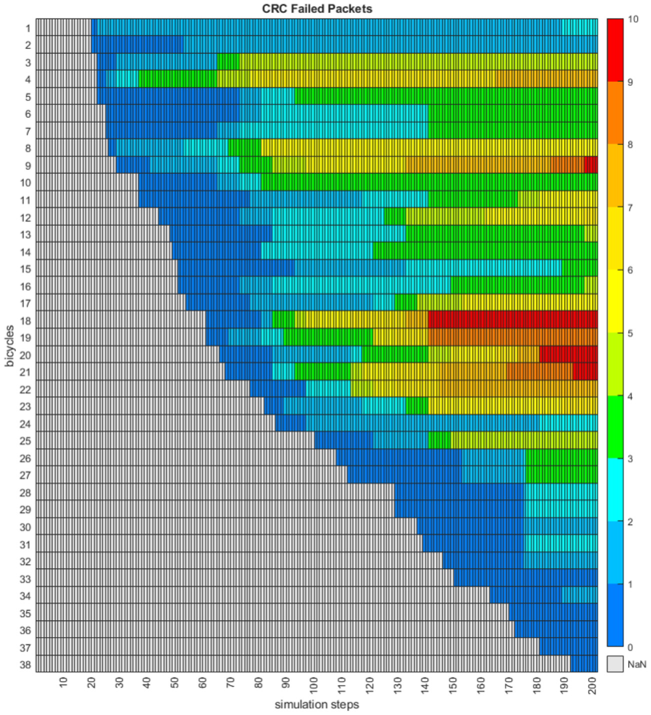

Fig. 5. CRC failed packets heatmap.

On the other hand, as it can be observed in the heatmaps the values of the dropped packets, packet collisions, and CRC failed packets showed a substantial difference compared to the low-density scenario where their values were 0. In the heatmaps for the dropped packets (Figure 4), packet collisions (Figure 6), and CRC failed packets (Figure 5), it can be seen that the results obtained for the first bicycles (bicycles 1 and 2) and the last bicycles (bicycles from 30 to 38) are lower. In the case of the first bicycles, this is due to them starting and remaining further apart from the other bicycles until almost the end of the simulation, which leads to them being with fewer bicycles surrounding them which causes less interference. For the bicycles that appear at the end of the simulation, the values of the dropped packets, packet collisions, and CRC failed packets are lower since those bicycles appear almost at the end of the simulation, which leads to those bikes sending fewer packages and therefor having a lower number of problems caused by the interference of other bicycles.

The realistic simulation of bicycles with SUMO has resulted in a representation that meets the expected behavior in terms of traffic

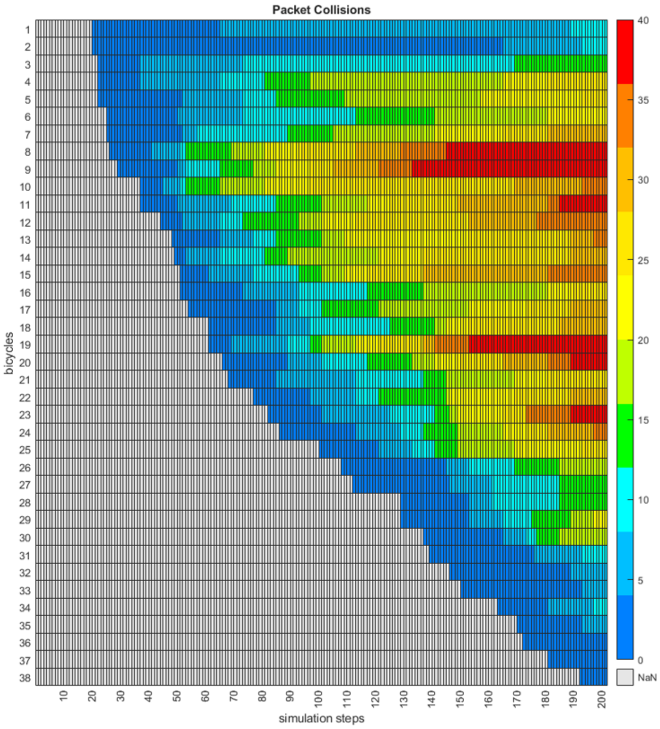

Fig. 6. Packet collision heatmap.

flow and movement patterns observed in the multitude of simulations performed. However, there were some problems when changing the parameters of the bicycles since any change would lead to the vehicle type changing from bicycle to car. In the case of a more complex simulation, it would be needed to use external plugins to enhance the simulation capabilities of SUMO, since the basic SUMO tools in areas such as intersections as it was proven by Ahmet-Sedar et all in [11].

7 CONCLUSION

The integration between SUMO and MATLAB has proven to be effective for the study of Bluetooth LE communications in urban environments with bicycle mobility. This methodology allowed a realistic representation of urban mobility and facilitated a detailed analysis of the impact of this mobility on wireless communications. Although it is true that it was necessary to implement functionalities that were not present in MATLAB in order to carry out the perfect synchronization between the positions of the bicycles and the Bluetooth LE nodes, it was necessary to implement functionalities that were not present in MATLAB in order to carry out the perfect synchronization between the positions of the bicycles and the Bluetooth LE nodes.

We tried to make the SUMO simulation as realistic as possible given the existing tools in the SUMO application, but since bicycle traffic is simulated using adapted versions of slow car models or fast pedestrian models for longitudinal movements and interactions [10], the results may not be as realistic as expected. As well the SUMO team also highlighted, that when a cyclist with the right of way enters an intersection, other cyclists aiming to traverse the internal link must hold back until the cyclist with the right of way has fully exited the intersection, despite there being adequate time and space for a safe crossing [10]. Another problem concerning the intersections pointed out in the article [11] is that SUMO's default model only allows cyclists to make direct left turns, which considerably reduces the simulation's realism.

From the outset, it has been intended to depict a dense, but realistic scenario. It is dense, but in countries like the Netherlands, it is highly probable. It has been avoided to go for a saturated scenario of hundreds of bicycles standing next to each other, which even if possible under certain circumstances would be extremely unusual. In such a scenario the study would not be very revealing since if we also set the advertising interval low enough it is obvious that the network would collapse.

On the other hand, in low bike density scenarios, as expected Bluetooth LE communications showed stable and efficient performance, with no collisions or errors.

The results in the high-density scenario have revealed that bicycle density has a significant impact on Bluetooth LE communications. In high-density scenarios, a noticeable increase in the rate of collisions and transmission errors was observed, clearly indicating increased congestion of the communication channel. At some nodes, the ratio of transmitted packets to collisions exceeded 25 percent. On average for those nodes, around 150 packets were sent at a rate of 1 packet every 0.1 seconds. As collisions increased at a node, doped packets and CRC Failed Packets also increased at that node. This is logical as there will be more congestion in the medium.

The number of collisions could be reduced by increasing the advertisement time Interval [18] and this would also reduce energy consumption, although the latter is not the subject of this study. On the other hand, the frequency range used to transmit Bluetooth LE is also used by other technologies such as Wi-Fi networks. We have not assumed the coexistence with other elements as well as other problems such as attenuation caused by the different physical elements of the environment.

To determine the suitability or otherwise of the measured communication quality it would be essential to take into account the requirements of each application. There will be applications that can afford to lose packets and have sub-optimal connection times that would be unthinkable for other more critical applications. However, despite this, the results obtained, taking into account that this is a scenario that could be common and without other types of interference, do not seem very encouraging to us.

8 FUTURE WORK

In our research, we executed steps of 0.1 seconds it would be useful to determine which is the ideal duration of a step so it doesn't compromise the accuracy of the results while reducing the amount of time and resources consumed by the simulations. In the future, it would be interesting to study the effects of other technologies such as Wi-Fi on BLE communication. Also, in our simulation, it wasn't taken into account the effects of the interference on the signal caused by obstacles such as cars, trees, buildings, or the body of the cyclist, this could be performed in future research. It could be also interesting to determine which is the most optimal location to locate the BLE device on the bicycle.

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