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PERFORMANCE OF D2D/NB-IOT COMMUNICATIONS IN URBAN AND SUBURBAN ENVIRONMENTS

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ABSTRACT

Smart cities are witnessing exceptional growth in their connections, increasing the need for *LPWA* communications, i.e. low-bitrate, coverage enhancement, ultra-low power consumption, and massive terminal access. *5G Narrowband-IoT*, has emerged to satisfy these requirements. Notwithstanding, it presents limitations in extreme coverage scenarios, where devices can lose connectivity unnecessarily. The addition of Device-to-Device (*D2D*), thus, connecting out-of-coverage devices with a base station through a relay, is a solid approach for mitigating these issues. More comprehensive performance and sensitivity analyses are required to achieve this goal. This study targets two typical scenarios, urban and suburban, measuring the impact of the duty cycle, path-loss, retransmissions and interference, regarding the expected delivery ratio, end-to-end delay, and the *QoS*. Our simulations show how the behavior of these quantities leads to a novel strategy to avoid disconnection.

1 INTRODUCTION

The smart cities paradigm aims to improve people's quality of life by leveraging information at the urban and suburban scale through the massive connection of heterogeneous objects to the Internet, i.e. the Internet of Things (*IoT*) (Santos et al. 2018; Zanella et al. 2014). This paradigm presents several challenges related to the quality of service (*QoS*), such as massive connectivity and coverage, communication quality, energy, and economic savings, among others.

In line with these aims, 5G Narrowband IoT (*NB-IoT*), a low power wide area (*LPWA*) communication technology, is designed to provide coverage to a large number of user equipment (*UE*) (Miao et al. 2018). *NB-IoT* uses an existing cellular spectrum and, to enable its usage, only a software upgrade is needed in each base station (*BS*) simplifying its deployment and adoption (Li et al. 2018). *NB-IoT* networks are gaining importance in practical deployments like smart city, eHealth, smart parking, smart bike sharing, smart metering, and tracking (Xu et al. 2018).

NB-IoT is particularly useful in sensor networks, where large sets of user equipment (*UE*) transfer small amounts of data for short periods. These devices can sense different magnitudes of the medium (Ammari 2014) and are capable of transmitting and storing these data. *NB-IoT* is suggested as a suitable technology for smart metering over a Smart Grid (Nair, Litjens, and Zhang 2018) where strategies related to *BS* foot-print adaptation and machine-to-machine communication can be used for dealing with latency issues about Outage Restoration and Management (*ORM*) alarm messages (Luján et al. 2020; Luján et al. 2019).

Although one of the main characteristics of this technology is wide coverage (near 15 km) (Li et al. 2018), it faces serious issues in extreme scenarios such as dense urban areas and long-distance com-

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munications (Zuloaga Mellino et al. 2019; Luján et al. 2020). To mitigate these drawbacks, different strategies based on optimizing shared channel radio resource consumption were proposed focusing on the selection of the link parameters: modulation and coding scheme (*MCS*), and the number of repetitions and retransmissions (Yu et al. 2017).

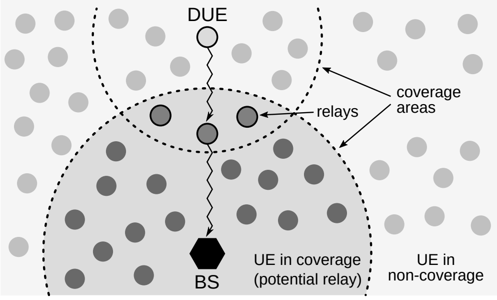


Figure 1: *NB-IoT/D2D* hybrid scheme. The base station (*BS*) communicates directly with some devices which are within its coverage area. A *UE* can act as a relay helping to reach the *BS* for the devices outside this area, thus extending the communications range.

On the other hand, Device-to-device (*D2D*) communication was suggested to address *NB-IoT* connectivity issues in extreme coverage scenarios (Li et al. 2018; Nauman et al. 2019). *D2D* provides more flexibility in terms of offloading traffic from the core network, increases spectral efficiency, and reduces the energy and cost per bit (Kar and Sanyal 2018). To illustrate this, Figure 1 presents a *D2D/NB-IoT* hybrid configuration scheme. A *BS* (black hexagon) provides service to a set of devices (dark gray circles) or *UE* in coverage. Outside the area covered by the *BS*, there is another set of *UE* that are unable to communicate directly with the *BS* (light gray circles), thus, the non-coverage *UE*. *D2D* establishes a two-hop route, connecting out-of-coverage devices with the *BS* using a relay, which is one of the *UE* that can be serviced by the *BS*. Figure 1 also shows the coverage area of a designated non-coverage *UE* (*DUE*, black-border light gray circle). Inside this area, there are three potential relays (black-border dark gray circles) through which communication with the *BS* can take place. The *D2D* strategy establishes how to select the relays considering different communication parameters, such as the surrounding interfering devices.

Three performance metrics are commonly used to analyze the behavior of a *D2D* scheme in unreliable communications networks: the expected delivery ratio (*EDR*); the expected communication delay, or expected end-to-end communication delay (*EED*); and the expected energy consumption (*EEC*) (Gu and He 2007). Particularly, two *D2D* communication schemes were proposed as routing extensions of *NB-IoT* systems (Li et al. 2018; Nauman et al. 2019), optimizing *EDR*, and *EED* using different relay selection strategies. Thus, *D2D* is proposed to favor coverage, connection quality, and massive communications in *NB-IoT* connections.

Regarding existing similar simulation tools, in (Abbas et al. 2020) the `NB-IoT` uplink scheduler and the traffic of periodic `IoT` applications are analyzed using a `Simulink`-based implementation. In (Li et al. 2018) a `Matlab` code is developed to study `D2D` communications as a routing extension to `NB-IoT` systems. Similarly, (Althobaiti and Dohler 2021) present a `Matlab`-based toolbox focused on `D2D` and `NB-IoT` which, among other features, includes the Physical (PHY), network, and application layers. These codes are based on proprietary software and are not available for public access, or their licenses prohibit copying and modifying the software. To the best of our knowledge, our proposal is the first open source proposal focused on the interaction of `NB-IoT` and `D2D` communications.

This study focuses on the variables that have a strong impact on system performance and are crucial for optimizing the connection quality.

1.1 Distance between devices

One of the factors influencing the quality of the signal is attenuation, which is the loss of strength of the emitted signal and is directly related to the transmission distance. The greater the distance, the greater the attenuation, and the worse the quality of the received signal. This raises the need to study how changing distances between devices impacts on D2D/NB-IoT solutions.

There are several technological options to support short-range wireless technologies enabling *D2D* communications (Kar and Sanyal 2018). Bluetooth 5 supports a maximum data rate of 50 Mbit/s and a range close to 240 m, WiFi Direct allows up to 250 Mbit/s rates and 200 m range while *LTE* Direct provides rates up to 13.5 Mbit/s and a range of 500 m. These data are useful to establish a framework for the configuration of *D2D* communication distances.

1.2 Obstacle density

When wireless devices emit signals, they do not always reach the receiver directly because there is a possibility that they will be reflected, diffracted, or refracted due to the obstacles in the environment where they travel. Depending on the obstacle density, these effects will have a greater or lesser impact on the quality of the signal. Three distributed algorithms are studied for estimating the strong impact of the obstacle density on the quality of the links (Srinivasa and Haenggi 2009), and hence, highlighting the importance of analyzing this variable to optimize the operation of wireless networks.

1.3 Transmission's scheduling

The duty cycle of the relays and the maximum number of retransmissions allowed are two distinctive parameters in the context of *D2D* communications. The duty cycle relates to the percentage of time a device stays in *D2D* mode and cellular mode. An increase in the *D2D* mode percentage will increase its effectiveness as a relay but decreases the opportunity to communicate with the *BS*. A trade-off value should be explored to optimize system performance.

On the other hand, the maximum number of retransmissions could guarantee the delivery of messages. When using retransmissions, each transmission block is transmitted repeatedly until its arrival is successful, and in every i_{th} transmission, the probability of successful delivery increases. However, by making more attempts to send the same message, more resources are consumed and more time would be spent, increasing the *EED*. This subtle balance between *EDR* and *EED* has to be explored for selecting the number of retransmissions to be used in a specific scenario.

1.4 Interfering device density

When several devices emit their signal simultaneously using the same channel they can generate interference in the reception of each other's signal (ElGarhy and Reggiani 2018). The more devices there are, the more likely the interference is to increase, and thus the quality of the signal will decrease. This emphasizes the need to explore how the increase of this density influences the communication efficiency in a *D2D* scheme.

In this work, we analyze the impact on communications performance in the following scenarios:

- Two typical environments: urban and suburban, represented by different obstacle densities and footprint radios of *BS* and *DUE*.
- Two transmission scheduling strategies: the variation of the relays' duty cycle and the maximum number of retransmissions.
- Interference conditions: the variation of the out-of-coverage device's density.

We define different *QoS* levels based on a combination of *EDR* and *EED* to analyze the simultaneous impact of devices' density and the maximum number of retransmissions. The variation of the relays' duty cycle is analyzed in all the scenarios. This simulation model allows us to explore parametric combinations to establish novel strategies to obtain reliable communications, defining if it is better to use relays or retransmissions according to the external environment. In particular, based on our simulation results, we propose a strategy to prevent communication disruptions when subtle environment perturbations generate a destructive effect in the delivery ratio.

This work is organized as follows: in section 2, the computational model is presented. The details of the different simulation scenarios and configurations used are shown in section 3. In section 4, the simulation results and the discussion are included. Finally, in section 5, conclusions are drawn.

2 MODEL

In this study, we model the communication channels using the Rayleigh fading model (Li et al. 2018; Nauman et al. 2019). The channel's gain between a receiver-transmitter pair is $h_{x,y}$, and it is assumed exponentially distributed with $exp(\mu)$. The received signal power at distance r from the transmitter is denoted as $h_{x,y}r^{-\alpha}$, where α is the path loss exponent (*PLE*). We assume all cellular links and *D2D* links share the same *PLE*. The noise power is assumed additive and constant σ^2. The value of α depends on the specific propagation environment (Rappaport 2002). In free space, α is equal to 2 (density of obstacles equal to zero), and with more obstructions, α will have larger values.

The signal-to-noise-plus-interference ratio (*SINR*) between the UE_x and UE_y, is obtained from the following expression (Andrews et al. 2010; Nauman et al. 2019):

$$SINR_{x,y} = \frac{h_{x,y}P_x r^{-\alpha}}{\sum_{t\in\phi_y, t\neq x} h_{t,y}P_t r_{t,y}^{-\alpha} + \sigma^2} \tag{1}$$

where P_x is the transmitter power of UE_x, r is the link distance between the UE_x and UE_y, and ϕ_y denotes the set of all UE_t, which interfere with the UE_y (UE_x is excluded as is the transmitter).

The probability of unsuccessfully transmitting a bit or bit error rate (p_b) is computed using the *SINR*. Considering the detection of a binary signal with additive white Gaussian noise, p_b can be expressed as:

$$p_b = Q(\sqrt{SINR}) \tag{2}$$

with $Q(\cdot)$ denoting the following function:

$$Q(x) = 0.5 \cdot \text{erfc}\left(x/\sqrt{2}\right) \tag{3}$$

The p_b, in turn, allows us to compute the packet delivery ratio (*PDR*), thus, the probability of successfully deliver a complete message or packet. It is assumed that each packet has a size of L bits and that it can be split into L/l parts, where each part shares the same *SINR* and p_b for all the l bits. Thus, the *PDR* of the i_{th} packet of size L_i bits can be expressed as:

$$PDR(i) = \prod_{j=1}^{L_i/l} (1 - p_b(i,j))^l \tag{4}$$

where $p_b(i,j)$ is the bit error rate of the j_{th} fragment of l bits of the i_{th} packet. The averaged *PDR* can be obtained using the following expression:

$$PDR = \frac{1}{W}\sum_{i=1}^{W}\sum_{j=1}^{L_i/l} (1 - p_b(i,j))^l \tag{5}$$

where W is the number of packets delivered.

In a *D2D* scheme, a non-coverage *UE* transmits its packages to the *BS* through a relay. If the transmission to the relay fails, retransmission to the same or different relay takes place. Once the relay receives the packet, it will try to send it to the *BS*. The order by which the relays are selected at each retransmission is called the *relay selection policy*. In actual networks, a *UE* should not try to retransmit a message indefinitely because it would negatively impact energy consumption and its overall performance. The number of *D2D* retransmissions should leave at least one communication slot for its cellular mode. If the package cannot be delivered using the defined maximum number of retransmissions, it will be discarded. The same will happen in the case of delivery between the relay and the *BS* (Li et al. 2018).

The expected delivery ratio, or *EDR*, for an out-of-coverage UE_x denoted by $EDR(x)$, is the expected *PDR* from the UE_x to the *BS* in two hops using a relay:

$$EDR = \sum_{i=1}^{N-1} \sum_{k=1}^{K} Q_{i,k}^{(x)} PDR_{k,BS_k}^{(N-i)} \tag{6}$$

where N is the maximum number of retransmissions (whose duration is τ each), K is the number of candidate relays for UE_x, and $Q_{i,k}^{(x)}$ is the probability that the packet will be successfully received in the i_{th} retransmission of the r_k relay, that is:

$$Q_{i,k}^{(x)} = \prod_{j=1}^{i-1} \left(1 - \sum_{m=1}^{K} PDR_{x,m} \delta_{j,m}^{(x)}\right) PDR_{x,k} \delta_{i,k}^{(x)} \tag{7}$$

where $PDR_{x,m}$ is the estimated *PDR* of the link between the UE_x and the relay r_m, and $\delta_{i,k}^{(x)}$ is the implementation of the relay selection policy for the UE_x returning 1 if the relay k is selected for the i_{th} retransmission and 0 otherwise. Also, $PDR_{k,BS_k}^{(N-i)}$ is the estimated *PDR* of the link between the relay r_k and its associated *BS*, with a maximum of $N-i$ retransmissions, i.e:

$$PDR_{k,BS_k}^{(N-i)} = 1 - (1 - PDR_{k,BS_k})^{N-i} \tag{8}$$

The expected end-to-end communication delay (*EED*) for an out-of-coverage UE_x is:

$$EED = \frac{\sum_{i=1}^{N-1} \sum_{k=1}^{K} Q_{i,k}^{(x)} PDR_{k,BS_k}^{(N-i)} (i\tau + ED_{k,BS_k}^{(N-i)})}{EDR} \tag{9}$$

where $ED_{k,BS_k}^{(N-i)}$ is the expected delay for the packet transmitted by the relay r_k to its linked base station, having a maximum of $N-i$ transmissions, which is:

$$ED_{k,BSk}^{(N-i)} = \frac{\sum_{l=1}^{N-i} l\tau (1 - PDR_{k,BS_k})^{l-1} PDR_{k,BS_k}}{PDR_{k,BS_k}^{(N-i)}} \tag{10}$$

NB-IoT introduces three kinds of coverage classes including normal coverage, robust coverage, and extreme coverage (Chen et al. 2017). Here we focus on the last coverage class for the performance evaluation of the *D2D*/*NB-IoT* hybrid scheme. Based on the *EDR* and *EED* we analyze three quality-of-services zones within the extreme coverage class: high, medium, and low. This qualitative classification is shown in table 1. The high *QOS* zone involves having high *EDR* and low *EED* values simultaneously, while *EDR* values below 0.1 and *EED* values above 30 are considered unacceptable. For our classification, we take the worst zone according to the table. For example, if in one case *EDR* would be *high*, but *EDR* is *medium*, the classification for that case would be *medium*.

Table 1: Qualitative classifications for *EDR* and *EED* to define quality-of-service in extreme coverage class.

EDR	[0.6, 1.0]	(0.2, 0.6)	[0.1, 0.2]
EED	[0, 12]	(12, 24]	(24, 30]
Quality	**high**	**medium**	**low**

For this work, we developed an open-source simulation tool that integrates *D2D/NB-IoT* communications. This tool is available at https://github.com/LICAR-UBA/NBIoT-D2D-Sim. The simulation code was executed in an `Ubuntu 18.04.4 LTS` system. The main simulation code was written in `C`, the compilation is assisted by `Makefile`, and the experiment setup script was written in `BASH`.

3 CASE STUDIES

Table 2: Case study parameters

Parameter	**Value (urban)**	**Value (suburban)**	**Unit**	**Reference**
Packet size (L)	336	336	bit	(Li et al. 2018)
Packet size chunk (l)	168	168	bit	
Rayleigh channel, μ	1	1		(Li et al. 2018)
Rayleigh channel, λ	1	1		(Li et al. 2018)
Relay density	2500	260	km^{-2}	Values in the range of those reported in (Jejdling 2020)
Non-coveraged *UE* density	150, 250, 350, 500, 600	1.0, 1.5, 2.0, 2.5, 3.0	km^{-2}	Values in the range of those reported in (Jejdling 2020)
PLE	3.0 to 3.8 (0.05 steps)	2.00 to 2.75 (0.05 steps)		
Effective *PLE*	3.5	2.3		
Effective duty cycle	0.2	0.2		(Li et al. 2018)
Duty cycles	10, 20, 30, 40, 50	10, 20, 30, 40, 50	%	
Effective Maximum retransmissions (N)	30	30		(Li et al. 2018)
Maximum retransmissions (N)	10 to 50 (2 points per step)	10 to 50 (2 points per step)		
BS radius	200	5000	m	(Bao et al. 2018)
DUE radius	150	450	m	(Li et al. 2018)
BS-to-DUE distance	250	5450	m	
DUE transmit power	13	13	dBm	(Bao et al. 2018)
Noise power (σ^2)	-79.95	-88.5	dBm	(Bao et al. 2018)
No. repetitions	0	0		(Li et al. 2018)

We define two typical scenarios to evaluate the *D2D* scheme: urban and suburban environments. The urban environment is characterized by short-distance communications (less than 300 m) and a high density of buildings representing the higher density of obstacles in the link channel. In this case, PLE varies between 3.0 and 3.8, with increases of 0.05. The *BS* footprint is set to a 200 m radius for cellular communication, and the *DUE* footprint is set to a 150 m radius for *D2D* communications. The *UE* density in the coverage area and, therefore, the relays density are set to 2500 UE/km^2 characterizing cities with a large number of devices served by each *BS*.

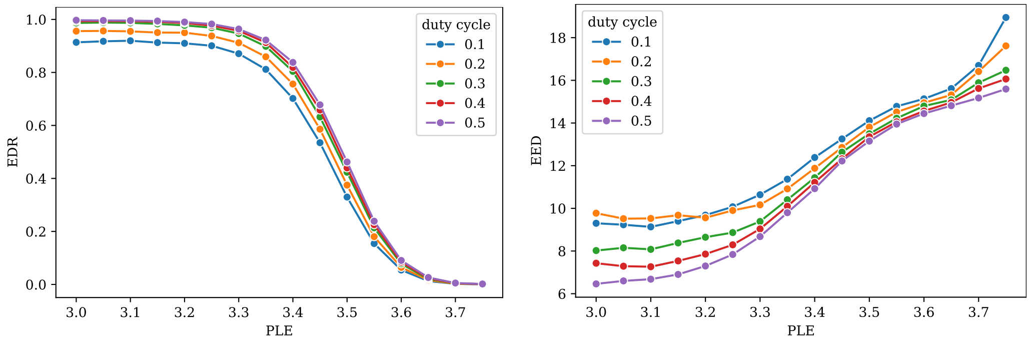
The suburban environment is characterized by long distances (more than 5000 m) with a low density of obstacles. For the suburban scenario, the variation of the *PLE* is between 2.00 and 2.75, with increases of 0.05. *BS* footprint is set to 5000 m radius, and that of the *DUE* is set to 450 m radius. The relay density was set to 600 UE/km^2, characterizing few devices served by the *BS*.

We assume that the *BS* controls the cellular communications and, therefore, there is no interference between the *UE* linked to the *BS*. On the contrary, the non-coverage devices interfere with each other due to the lack of a *BS* control scheme.

As we aim to analyze the impact of *D2D* communications, we configure each scenario having a single *BS* and centered in a *UE* without coverage, which we called *DUE*. *DUE* and *BS* are located having an intersection coverage area where the relays could be found. The devices inside the BS footprint and also within range of *DUE* become potential relays.

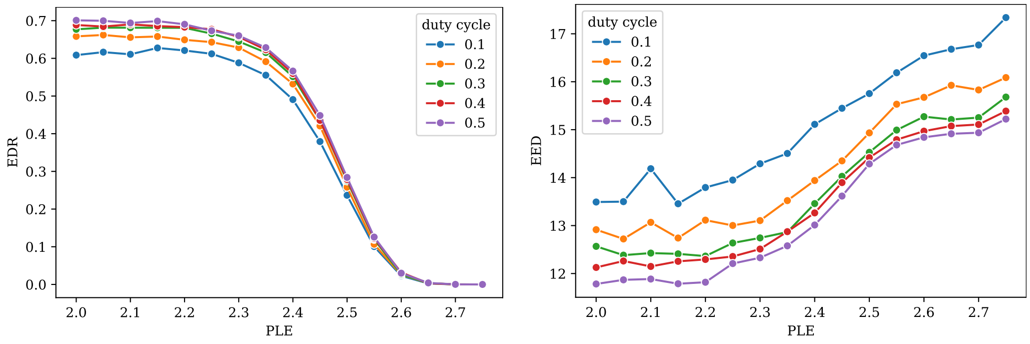
In each simulation, the topology is generated by randomly locating each *UE*, in and out of coverage, using a uniform distribution. For each case, 200 topologies are studied and 1000 instances per topology are executed: 500 packages of two blocks each. The duty cycle is varied from 10 % to 50 %, with steps of 10 % between them. Table 2 shows the relevant parameters considered in each case.

4 RESULTS AND DISCUSSION



(a) Urban Scenario

(b) Urban Scenario



(c) Suburban Scenario

(d) Suburban Scenario

Figure 2: Impact of *PLE* increment in the *EDR* and *EED* with different duty cycles in urban (device density is 150 UE/km^2) and suburban (device density is 1 UE/km^2) scenarios. The maximum number of retransmissions is set to 24.

Figure 2 shows the behavior of the *EDR* and *EED* in the urban and suburban scenarios regarding the *PLE*, for different duty cycles. For the urban case, the device density is set to 150 UE/km^2, and for the suburban case, it is set to 1 UE/km^2 while the maximum number of retransmission is set to 24 for both scenarios. As can be seen in all figures, the *EDR* decreases and the *EED* increases with increasing *PLE*, for each duty cycle. This is explained by the fact that larger *PLE* values depict environments with higher obstacle density and attenuation, and therefore lower connection performance, thus, lower *EDR* and higher *EED*. Figure 2 also shows that lower duty cycle values are associated with slightly lower *EDR* and higher *EED* values, revealing that only small changes are seen for duty cycle values as large as 50 %.

In figures 2(a) and (b), within the analyzed *PLE* range (3.0 to 3.7), the *EDR* rapidly drops to zero, and the *EED* grows abruptly, unveiling that a *PLE* lower than 3.4 is needed to achieve package losses of less than 20 %, minimizing the delay. A *PLE* value equal to or greater than 3.6 represents a challenge to the communications system as the loss of packages strongly affects it.

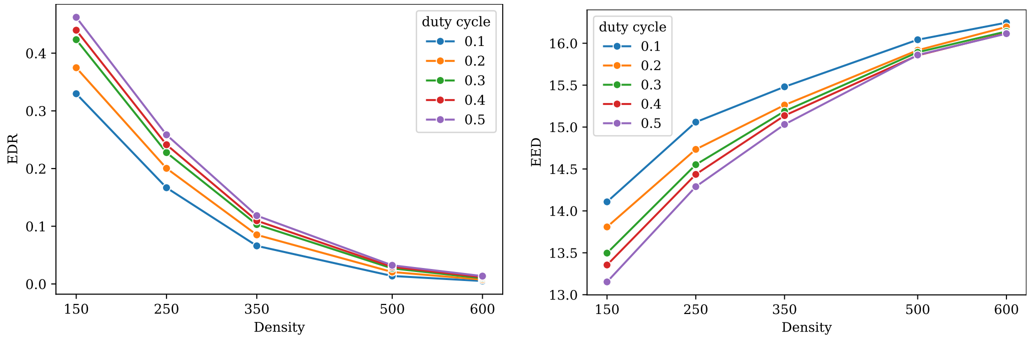
On the other hand, for the suburban environment in Figures 2(c) and (d), with lower *PLE* values (2.0 to 2.7), the *EDR* smoothly decreases up to a 2.4 *PLE*, since it abruptly drops to zero, exhibiting that just a short *PLE* range makes the communication plausible. The *EED* also grew significantly, by 50 % in the range analyzed, but much less than in the urban case.

Figure 3 shows the behavior of the *EDR* and *EED* in urban and suburban scenarios, for different duty cycles, focusing on the out-of-coverage *UE* density (i.e. those *UE* that can cause interference during the *D2D* communications). For the urban case, the *PLE* is set to 3.5, and for the suburban case it is set to 2.3 while and the maximum number of retransmission is set to 24 for both scenarios.

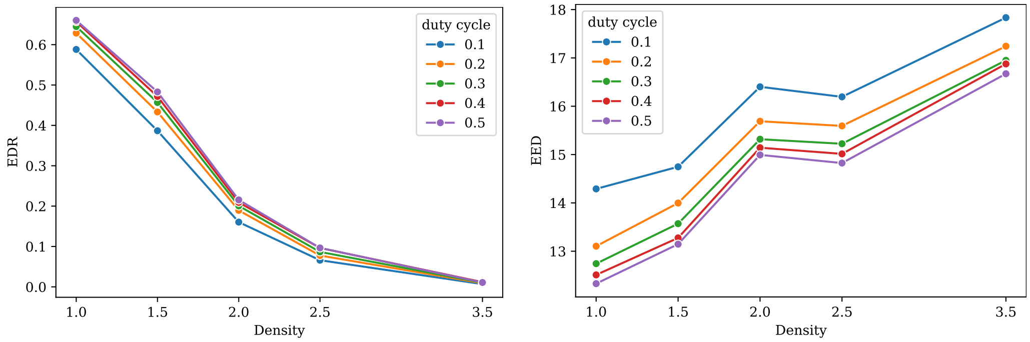
As the *UE* density increases, for each duty cycle, the *EDR* decreases and the *EED* increases. This is because the larger the number of out-of-coverage *UE*, the greater the interference, thus, the lower the communication performance.

Analogously to the *PLE* analysis, Figure 3 shows that higher duty cycles cause a small communication performance enhancement, thus, higher *EDR* and lower *EED*.

We observe in Figure 3(a) that the *EDR* highest values are in the range from 0.3 to 0.5 for the lowest analyzed density, 150 UE/km^2, indicating that the interference caused by these devices makes the communication poor. On the other side, in Figure 3(c), the lowest analyzed density makes communication very challenging with approximately 35 % of packet losses.



(a) Urban Scenario (b) Urban Scenario



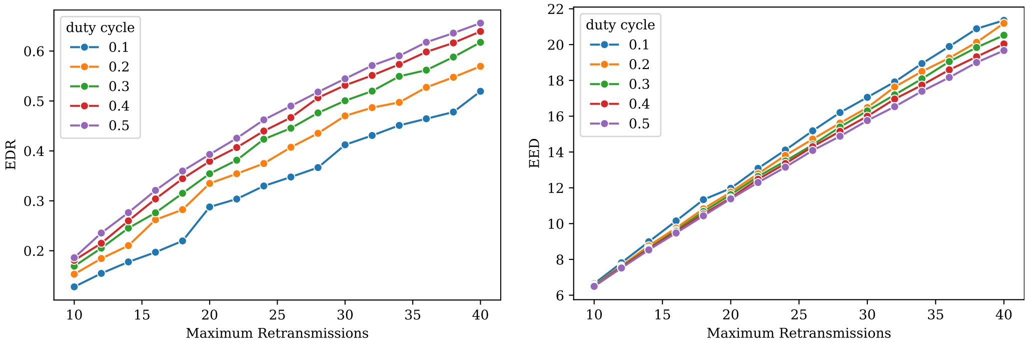
(c) Suburban Scenario (d) Suburban Scenario

Figure 3: Impact of out-of-coverage *UE* density in the *EDR* and *EED* for different duty cycles, in urban (*PLE* is 3.5) and suburban scenarios (*PLE* is 2.3). The maximum number of retransmissions is set to 24.

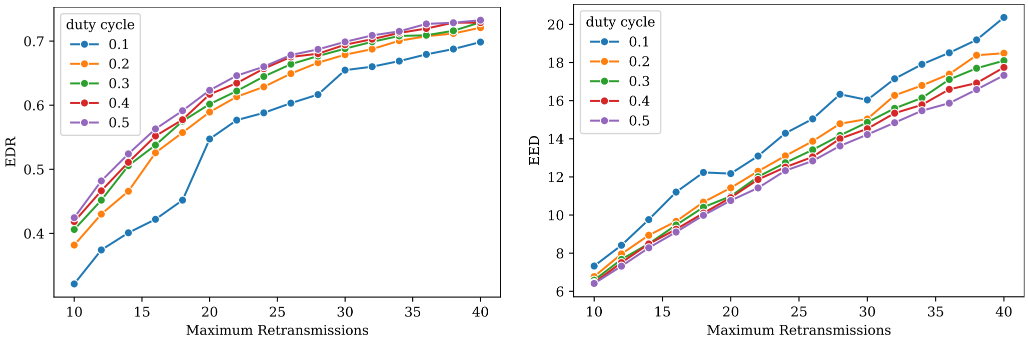
Figure 4 shows the behavior of the *EDR* and *EED* in the urban and suburban scenarios regarding the maximum number of retransmissions, for different duty cycles. For the urban case, the *PLE* is set to 3.5 and device density to 150 UE/km^2, and for the suburban case, it is set to 2.3 while device density to 1 UE/km^2. Concerning retransmissions, *D2D/NB-IoT* integration uses an acknowledged service, i.e., each packet sent by the *DUE* is individually acknowledged by the *BS*, through the relay. If the packet has not arrived within a specified interval (less than τ), it can be retransmitted. This kind of service is useful for noisy channels. While it may be inefficient, in unreliable wireless channels it is well worth the cost (Tanenbaum and Wetherall 2010).

Figure 4 reveals a trade-off between *EDR* and *EED*, the retransmission increment will increase the probability of successfully deliver a complete message, but it will also increase the communication delay. Moreover, a large number of retransmissions are needed to reach high *EDR* values. In this model, the maximum *NB-IoT* delay (i.e. EED equals 20) allows a maximum number of retransmissions of near 40.

In line with the previous analysis, Figure 4 also shows that the duty cycle does not significantly impact the communication performance providing small *EDR* increments and *EED* decrements.



(a) Urban Scenario (b) Urban Scenario



(c) Suburban Scenario (d) Suburban Scenario

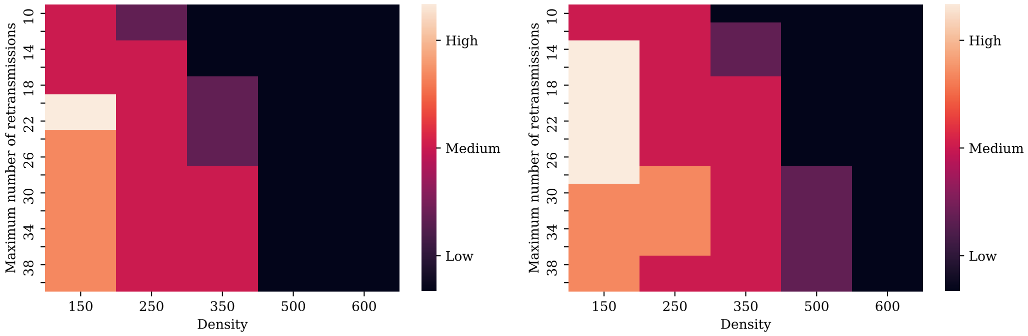
Figure 4: Impact of maximum number of retransmissions in the *EDR* and *EED* for different duty cycles in urban (*PLE* is 3.5 and device density is $150\,UE/\text{km}^2$) and suburban (*PLE* is 2.3 and device density is $1\,UE/\text{km}^2$) scenarios.

Coverage heatmaps show the zones that can be served using each parametric combination. For example, Figure 5 shows a *QoS* heatmap of the most prominent cases analyzed based on the definition presented in table 1. The best quality zones (lighter colors) correspond to both higher *EDR* and lower *EED*, while darker colors represent lower quality.

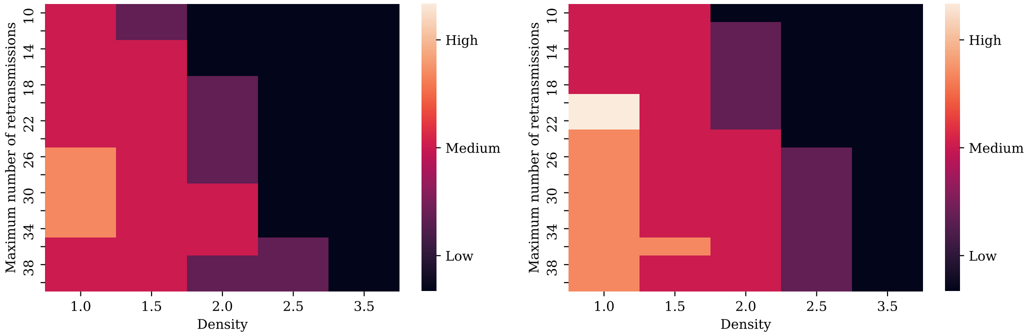
For the urban environment, *PLE* is set to 3.4, while for the suburban environment, it is set to 2.3. Two extreme duty cycle values are shown for both scenarios (0.1 and 0.5). In all the cases, the out-of-coverage *UE* density, ergo the interference, is the variable with the greatest impact. The number of retransmission should largely increase to compensate for the amount of interference generated by the devices. There are only a few combinations of density and retransmissions which enable good quality communications, strikingly increasing the maximum number of retransmissions does not guarantee a better quality in communications.

For both urban and suburban scenarios, good and medium quality zones are denoted by low-density values while keeping the maximum number of retransmissions not above 30.

Finally, Figures 2(a) and (b) show that EDR has a strong sensibility to *PLE* variations. In these cases, when *PLE* reaches a threshold value dependent on the considered environment, EDR sharply decreases to almost zero. This highlights the role of *PLE* in this hybrid *D2D/NB-IoT* proposal when compared to the rest of the parameters (like duty cycle and number of retransmissions). While in Figures 2(a) and (b) EDR drops to zero independently of the duty cycle, in Figures 4(a) and (c) EDR effectively increases to values that make communication feasible when more retransmissions are employed. Despite both mechanisms could be considered to improve EDR when *UE* device density has not reached saturation (see darker areas in Figure 5), the duty cycle cannot compensate for the negative effects of *PLE*. This naturally leads us to propose the following: when small environmental perturbations generate strong communications disruptions, it is advisable to switch to a retransmission-driven scheme. Although potentially having the disadvantage of reaching the maximum delay allowed by *NB-IoT*, they could guarantee the connection of several devices in extreme coverage due to its robustness concerning high *PLE*.



(a) PLE=3.4 and duty cycle=0.1 (b) PLE=3.4 and duty cycle=0.5



(c) PLE=2.3 and duty cycle=0.1 (d) PLE=2.3 and duty cycle=0.5

Figure 5: The impact of out-of-coverage *UE* density and the maximum number of retransmissions on extreme coverage class *QoS* based on EDR and EED, for urban and suburban scenarios.

5 CONCLUSIONS

This study analyzes the use of *D2D* communication to extend the range of *NB-IoT* in out-of-coverage scenarios. We evaluate the impact on the communication performance considering transmission scheduling (duty cycle and maximum retransmissions), environment (urban and suburban), distances between devices, and interference generated by other devices.

As expected, increasing the maximum number of retransmissions has a direct benefit on the *EDR*, but also negatively affect the *EED*, since it stimulates the consumption of more resources and increases the delay. Large values of the *PLE* degrade the communication quality, strongly decreasing the *EDR* and increasing the *EED*. e.g., in the urban environment, a *PLE* above 3.56 caused an *EDR* below 0.2, and in the suburban environment, a strong *EDR* decay is found when the *PLE* surpasses 2.5. Furthermore, the *UE* density, which is directly related to the interference between devices, showed a major impact on the communication performance, emphasizing the need for new protocols to handle the interference and access to the medium in *D2D*/*NB-IoT* coupled systems. In all the analyzed cases, an increase of the duty cycle by up to 50 % of the communication time produces a slightly positive impact on the performance measurements of about 10 %.

Qualitative zones of *QoS* in the extreme coverage class were defined combining classification ranges of *EDR* and *EED*, and considering different maximum number of retransmissions and densities. These zones showed how quality changes with different parametric combinations and support the design of *D2D* schemes once the environment has been determined.

Finally, this analysis revealed a straightforward strategy to mitigate communication disruptions in this hybrid *D2D*/*NB-IoT* system. In the event that small changes in the environment, thus in the *PLE*, generate strong delivery ratio losses, and the *UE* density has not reached saturation, it is advisable to switch to a retransmission-driven scheme. The duty cycle slightly contribute to the communication enhancement while the retransmissions are robust with respect to the *PLE* as well as present a remarkable positive impact on the communication quality. As a disadvantage, depending on the *PLE*, this could require reaching the maximum delay allowed by *NB-IoT*, but as an advantage, a large number of devices in extreme coverage would avoid being disconnected. We hope that these results will have an impact on the design of the future *D2D*/*NB-IoT* integrated infrastructure.

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