PERFORMANCE ANALYSIS OF ENERGY OPTIMIZED LTE-V2X NETWORKS FOR DELAY SENSITIVE REAL-TIME SERVICES

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ABSTRACT

Energy-efficient relaying technology in multi-hop data transmission can help the challenges faced in cellular Vehicle-to-Everything (cellular-V2X) communication. However, due to high demand of emergency service requirements of the systems such as Public Protection and Disaster Relief (PPDR), National Security and Public Safety (NSPS), Intelligent Transport System (ITS) etc., least energy consumed user equipment (UEs)/Vehicular-UEs are required which can either run real-time applications or relay the application data. To support these scenarios, we present a high way based system model in rural area and enhance its scope for applying single-hop direct, relay assisted multi-hop cellular-V2X and Store-Carry-Forward (SCF) modes of uplink data transmission. We compare the performance of three modes of transmissions in terms of overall energy consumption and overall transmission delay with specific delay constraints of VoIP and video applications. With the varying cell radius and irrespective type of applications, our numerical results, validated with ns-3 show that, least energy is always consumed in SCF mode due to its inherent property but applications suffer a lot due to high delay incurred whereas single-hop direct mode shows the reverse. When compared with cellular-V2X mode, overall transmission delay for single-hop direct mode is acceptable within cell radius 600m but beyond that, relay assisted multi-hop cellular-V2X mode always outperforms (with low latency and moderate energy consumption).

KEYWORDS

V2X communication, Energy efficiency, Direct communication, Store-carry-forward, Delay sensitive.

1. INTRODUCTION

With the exponential growth of high data rate demand, the next-generation wireless networks have been put under pressure to offload mobile data [1][4] and simultaneously include cellular-V2X (as Vehicle-to-Everything) communication. Cellular-V2X is a promising technology providing the requirements of public safety services such as Public Protection and Disaster Relief (PPDR), National Security and Public Safety (NSPS), Intelligent Transport System (ITS) etc. This emerging technology aims to fulfil the requirements of new set of applications with optimized energy efficiency to enhancements of road safety and traffic efficiency by enabling reliable and low latency services. Thus, cellular-V2X is highly suitable for providing emergency services which require delay sensitive networks, supporting real time and interactive applications such as audio and video calls, Internet browsing etc. Moreover, energy consumption of the user equipment (UE) is surprisingly increasing with the rapid growth of bandwidth-hungry applications. Due to limited battery power constraint of UE/vehicular-UE (VUE), performance of the system affects the quality-of-experience (QoE) of the users [5]. Hence, energy efficiency for handheld equipments (with limited battery power) has become a key performance indicator (KPI) of the cellular system which draws attention from research community to industry.

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As known, components of V2X communication include not only the communication between vehicles as V2V but also communication between vehicle and infrastructure as V2I, vehicle and pedestrian as V2P, and vehicle and network as V2N (shown in *Figure 1*). All components of V2X communication enable VUEs to communicate with a higher data rate for transmitting its cached data, roadside information such as accident, speed limit, etc. quickly [6]. Thus, quality of the effective communication provides high traffic safety and high quality-of-service (QoS) by minimizing latency and maximizing the reliability of the network.

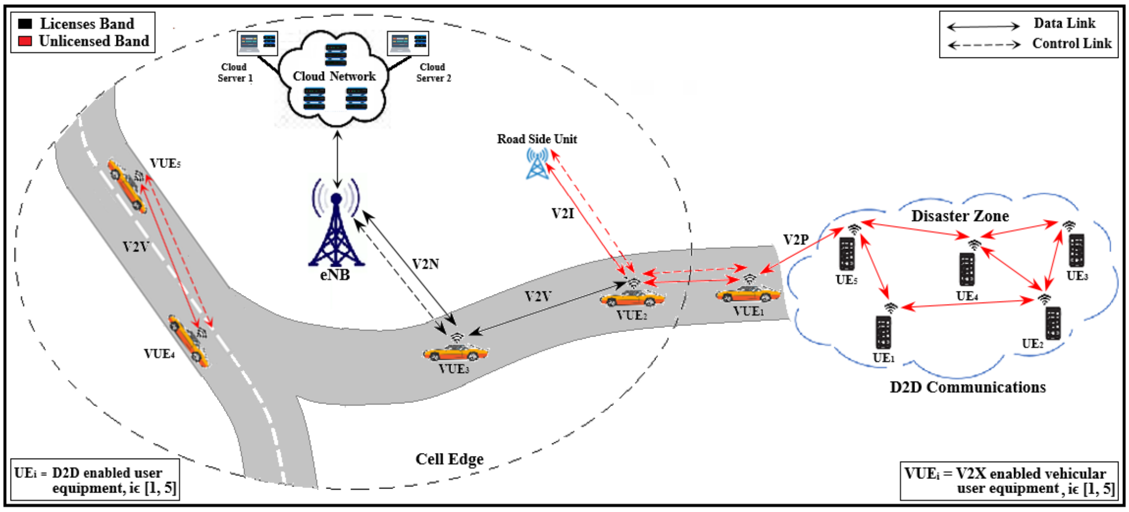


Figure 1. Use case with various components of V2X communication used in Public Safety Networks

In-coverage UE/VUE can directly communicate to eNB (in a single hop transmission) resulting in high energy consumption, high end-to-end delay for long-distance communication. Furthermore, direct mode of transmission increases network load when transceivers are at the cell edge. In contrast, cellular-V2X mode can alleviate the issues of single-hop direct communication. In this mode, VUEs can play a dual role i.e., *1.* they can be a source/destination at the end of the entire communication or *2.* they can act as relays for receiving, processing, and forwarding data. Relaying data reduces power consumption of the devices in one side and in other side, it decreases latency which has potential impact on applications running at the ends. Significant performance of out-of-coverage V2X mode is also seen when compared with in-coverage V2X mode. The later mode cannot be intervened by eNB which results autonomous resource selection based on sensing the environment. Thus, this mode may suffer from significant collisions and interferences in a dense environment but still it is widely accepted for multi-hop short range communications. Due to unavailability of the VUE in the proximity, store-carry-forward (SCF) mode of transmission is also used as another competent scheme. Though SCF mode, as a derived mode of cellular-V2X, is well-known least energy consumption scheme but it incurs high delay [7].

In general, VUE (as mobile relay compared to UE as the stationary relay) broadens the scope of seamless communication due to availability and mobility in high ways. Consequently, VUE can help in providing emergency requirements of Public Safety Network (PSN) services depending on efficient mission-critical applications such as voice, and video communications between first responders/receivers and victims. Areas belonging to natural disasters such as earthquakes, floods, tsunamis, hurricanes etc. demand emergency service requirements with immediate effect. Due to communication infrastructure being often damaged by natural calamities to large extent, made services unavailable or at least heavily congested, the stationary UEs in newly formed adhoc network may use cellular-V2X/SCF mode of transmission for sending information to traditional network via relay-assisted VUEs (as shown in the use case of *Figure 1*).

The main *objective* of this article is to *find out the best suitable mode of transmissions among single-hop direct mode, SCF mode, and relay-assisted multi-hop cellular-V2X mode by optimizing the overall energy consumption of the UE and/or VUEs and average transmission delay (from UE to eNB). The goal also includes to minimizing the power consumption in uplink (UL) data transmission with the delay constraints of various delay sensitive applications such as VoIP and video.*

To optimize energy consumption with specific delay constraints, we first present a system model and enhance its scope in a high way platform through rural areas. Second, by exploiting VUE as mobile relay, we apply traditional single-hop direct (to eNB), multi-hop cellular-V2X, and SCF mode of UL transmission on the enhanced system model. Third, based on numerical results, validated with *ns-3*, we measure overall energy consumption and delay metric for three modes of transmissions with the respective delay constraints of VoIP, and video applications.

The rest of this paper is organized as follows. In section 2, some background research works related to the topic of the article with the overview of their contributions are discussed. We present a system model and enhance it over the proposed scenario and formulate the problem in section 3. Simulation and numerical results with the analysis and comparison of the performances of three modes of data transmissions are discussed in section 4. Section 5 concludes the article and finally, section 6 gives some future research directions.

2. RELATED WORKS

To use the potential benefit of V2X communications, many works have been done on PSN (especially in ITS platform) in [5] and [8]-[12]. Authors in [5] formulate and propose an efficient solution methodology of optimization problem for minimizing the total power consumption by associating VUE. In [8], authors propose a hybrid communication approach using LTE and DSRC (i.e., 802.11p) for supporting high bandwidth and reliable applications of road safety and traffic efficiency such as video streaming. A new protocol architecture based on V2X communications has been suggested in [9]-[10] to avoid traffic jam at intersections. To improve the packet reception probability by reducing access latency and increasing high reliability, non-orthogonal multiple access has been exploited in [11]. For safety applications, authors of [12] improve reliability and reduce the latency of V2X communication by optimizing the network performance against signal power and delay constraints. In communications between users and vehicles on a highway scenario, they consider orthogonal resource block allocation and show significant performance gain.

Relay based multi-hop cellular networks (MCNs) concept is exploited in [13]-[15] to increase the efficiency of energy consumption in great extent for delay-tolerant applications. Authors in [13] propose a context-based opportunistic forwarding scheme (i.e., SCF) using location based optimum mobile relaying in two hop scenario for MCNs with D2D communications and show significant energy benefits for delay tolerant services by comparing with other forwarding schemes and traditional single-hop cellular communication. In [14], authors use the MCN concept to dramatically reduce the energy consumption of eNB and UE both, by exploiting vehicles as mobile relay in cellular network. The key concept in [15] is to search the next mobile relay within its short transmission zone in MCN. If the next mobile relay is found, the message is immediately forwarded otherwise it is carried. Based on the approach, authors reduce the energy consumption compared to traditional single hop communication. To extend cellular coverage, multi-hop D2D architecture on ISM band (using 802.11) is proposed in [16]. In this, authors also propose a modified Optimized Link State Routing Protocol (OLSR) based proactive routing, i.e., cell-OSLR to improve QoS of 4G/5G based applications.

In [7] and its extension [17], energy-efficient V2X communication has been proposed and analysed over LTE networks. In their articles, authors compare their proposed optimal resource allocation based V2X enable transmission and show their proposed scheme is more energy conserving than traditional direct transmission, decoding-and-forwarding (DF) based transmission and opportunistic SCF transmission with varying cell radius.

All existing works show an immense potentiality of V2X communications in PSNs (including ITS). *However, no such extensive investigations made in the recent past on optimal energy efficiency with delay constraints for delay sensitive applications which is crucial not only in the performance of road safety and traffic efficiency applications but also helps in providing the requirements of emergency services fast.*

3. Overview of Cellular-V2X and SCF Modes of Transmissions

3.1. Cellular-V2X mode

For being an advance low latency communication technology, V2X mode is exhaustively used in road transportation system to exchange information with other vehicles, pedestrian, infrastructure, network etc. Due to several limitations of Dedicated Short Range Communication (DSRC), such as unreliable broadcasts, short range communication etc., cellular-V2X has been evolved in LTE and 5G-NR architectures (in 3GPP released 14 and 16 respectively) to meet the traffic safety requirements such as high capacity, low latency, and long-range communications. From the resource scheduling perspective, LTE-V2X supports two modes named as LTE-cellular-V2X and LTE-direct-V2X (as Transmission Mode 3 and Mode 4 respectively). In both the approaches, Cooperative Awareness Message (CAM) is periodically broadcasted by a VUE to its neighbours to inform about its identification, state, velocity, location, public safety information etc. In LTE-cellular-V2X, centralized scheduling is used over Uu interface with 1.8-2.0 GHz band which is fully controlled by eNB. This mode of communication is operated (in UL and downlink (DL)), when a VUE is within the coverage of eNB. On the other hand, LTE-direct-V2X uses distributed scheduling approach over PC5 interface with 5.9 GHz band. As no involvement of eNB is required, LTE-direct-V2X mode can be operated in-coverage as well as out-of-coverage of eNB (using SL communication in PSSCH and PSCCH channels). LTE-direct-V2X (as cellular-V2X Mode 4) uses SC-FDM to cover larger transmission range with limited power. A VUE (using both dedicated and shared band in LTE-direct and LTE-cellular respectively) must need two individual transceivers otherwise single transceiver is sufficient for both the modes with shared band. Thus, the cellular-V2X mode of transmission not only improves application reliability but also conserves energy compared to direct transmission.

3.2. SCF mode

Another well-accepted energy efficient mode of transmission in the domain of V2X communications is SCF. Unlike cellular-V2X mode, SCF mode of transmission takes place in a chunk of data rather than on a per-packet basis. Applications where delay is not a crucial constraint such as file transfer, email, audio/video on demand etc. can run smoothly using SCF mode of transmission. This mode is not only a delay feeding but also a highly energy conserving mechanism. During prolonged carry phase of SCF mode, instead of transmission, data are transported which results significant energy saving. *Thus, for being highly energy optimized, this* *mode of transmission is considered in this article.* In contrary, all real time applications such as IP telephony, video conferencing and interactive applications such as web-access, remote login etc. suffer a lot in this mode. Moreover, SCF mode of transmission internally uses V2X mode in terms of V2P and V2I while receiving text/data from UE and uploading to eNB respectively. The store and followed by carry operations of SCF mode also reduces the energy consumption by minimizing the required internal nodes-processing and protocol overhead. For more, readers may study [13]-[15].

4. System Model and Problem Formulation

In this section, we present a highway based system model and formulate the problem to measure energy consumption and overall transmission delay due to the transmission of VoIP/video data from an UE (which is almost at the cell edge) to eNB in single-hop direct mode, multi-hop cellular-V2X mode, and SCF mode of transmissions. Various notations used in the problem formulation and their meanings are given in Table I.

Table I. Nomenclature

Notations	Meanings	Notations	Meanings
ω	Antenna characteristics	h_{eNB}	Antenna height of eNB
v	Velocity of the vehicle	h_{UE}	Antenna height of UE
r	Radius of the cell	p_{max}	Max. transmit power of UE
α	Path loss constant	p_d	Transmit power of UE
Ψ	Noise power	p_c	Circuit power of UE
M	VoIP/video data size	B	Channel bandwidth
w	Width of the road	D_{max}	Max. transmission delay
$r_{UE\text{-}eNB}$	Distance between UE and eNB	n	Effective no. of vehicles in V2V communication
$r_{V\text{-}V}$	Distance between vehicle and vehicle	$p_{UE\text{-}V}$	Transmit power of UE to vehicle
$s_{UE\text{-}V}$	Slant height between UE and vehicle	$p_{V\text{-}V}$	Transmit power of vehicle to vehicle
$s_{V\text{-}eNB}$	Slant height between vehicle and eNB	$p_{V\text{-}eNB}$	Transmit power of vehicle to eNB
d_{max}	Max. transmission range of V2V communication	$T_{UE\text{-}eNB}$	Transmission delay from UE to eNB
$T_{V\text{-}eNB}$	Transmission delay from vehicle to eNB	$T_{UE\text{-}V}$	Transmission delay from UE to vehicle
E_i	Energy consumed in i^{th} phase, $i \in \{1, 2, 3\}$	$T_{V\text{-}V}$	Transmission delay from vehicle to vehicle

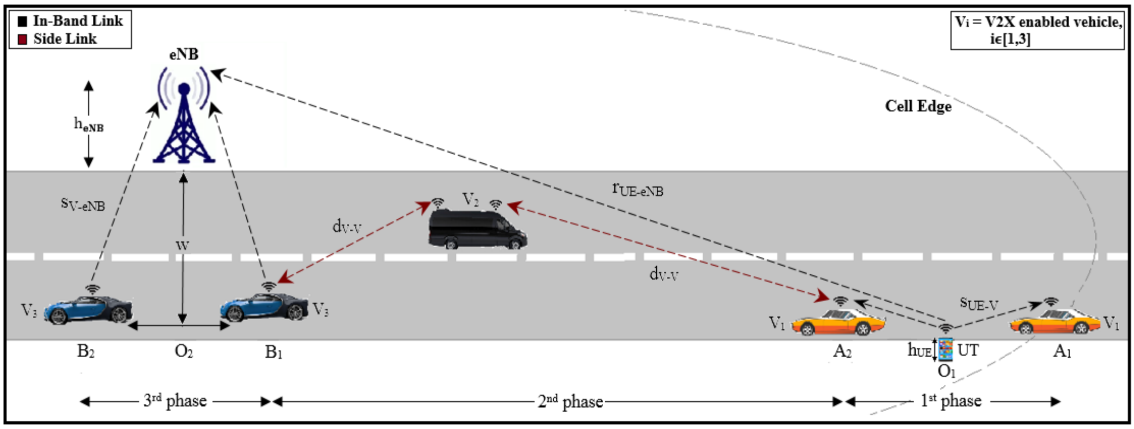


Figure 2. High way based system model supporting various modes data transmissions

In the system model (shown in *Figure 2*), we assume a two-way highway road (in rural areas) where a stationary UE is at the LTE-cell edge with radius r (i.e., r_{UE_eNB}) and the vehicles (functioning as mobile relays) move along the road towards/away from UE at a constant velocity v. We further assume that the UE (as an intelligent relay) is either a part of an ad-hoc network where VoIP/video data with size M, is generated requiring for emergency services or itself a source of data. By using relay assisted vehicles (i.e., VUE), data can be transmitted to infrastructure based network using any three modes of transmissions.

4.1. Energy consumption in single-hop direct mode:

For calculating achievable data rate in conventional UL transmission, basic Shannon capacity formula is stated as:

$$K = B\log_2(1 + \mathrm{SINR}) \tag{1}$$

Following [17], SINR (Signal-to-Interference-Plus-Noise-Ratio) is calculated as:

$$\mathrm{SINR} = \frac{\omega p_d \varsigma}{\Psi^2 r^{\alpha}_{UE-eNB}} \tag{2}$$

where, $\varsigma = \frac{-1.5}{\ln(5.BER)}$ (BER as bit error rate).

Substituting Eq. (2) in Eq. (1), the achievable data rate corresponds to transmit power is obtained as:

$$K(p_d) = B\log_2(1 + \frac{\omega p_d \varsigma}{r^{\alpha}_{UE-eNB}\ \Psi^2}) \tag{3}$$

where, K is a function of p_d.

Hence, using Eq. (3), direct UL transmit power of UE for data rate K can be obtained as:

$$p_d(K) = (2^{\frac{K}{B}} - 1)\frac{\Psi^2 r^{\alpha}_{UE-eNB}}{\omega \varsigma} \tag{4}$$

So, p_d is a strictly monotonically increasing function of K (provided all other factors remain constant).

Thus, overall energy consumption (E_d) in UL single-hop direct mode of transmission of UE is formulated as:

$$\min_{p_d}(E_d) \triangleq (p_d + p_c)\frac{M}{K} \tag{5}$$

The objective function in Eq. (5) satisfies the constraints:

$$p_d \leq p_{max} \tag{5.1}$$

and,

$$\frac{M}{K} \leq D_{max} \tag{5.2}$$

In eq. (5.1) and (5.2) ensure the power transmission and transmission delay within the range of respective thresholds of cellular network.

As Eq. (4) is a strictly monotonic function and also $\frac{M}{D_{max}} \leq K(p_d)$, we get $p_d\left(\frac{M}{K}\right) \leq p_d$. Moreover, at p_{max} the Ineq. (5.2) also satisfies the inequality: $\frac{M}{K(p_{max})} \leq D_{max}$.

Thus, modifying Eq. (5), the objective function is reconstructed as:

$$\min_{p_d}(E_d) \triangleq (p_d + p_c)\frac{M}{K(p_d)} \tag{6}$$

subject to,

$$p_d\left(\frac{M}{D_{max}}\right) \leq p_d \leq p_{max} \tag{6.1}$$

4.2. Energy consumption in multi-hop cellular-V2X mode

In cellular-V2X mode, data are first transmitted by UE to a nearby vehicle (i.e., relay assisted VUE) moving towards eNB, and then receiving VUE decodes, processes, and forwards the data to the next VUE. Thus, the transmission repeats in multi-hop until the data are forwarded by the VUE to eNB in close proximity. Hence, overall transmission in this mode can be divided in three following phases as shown in *Figure 2*.

- *1st phase:* As VUE is within the coverage, UE directly transmits data to VUE (which is nothing but a V2P transmission and spanned from A_1 to A_2).
- *2nd phase:* VUEs move gradually towards/away from the eNB and transmission in this phase is due to relaying data in a multi-hop fashion (which is nothing but a multi-hop V2V transmission and spanned from A_2 to B_1).
- *3rd phase:* As and when eNB is in the close proximity of the VUE, the received data is directly sent to eNB by UL transmission (which is nothing but a V2I transmission and spanned from B_1 to B_2).

4.2.1. Energy consumption in 1st phase of cellular-V2X mode

Since, UE directly uploads the data to its nearest VUE, the energy consumption (E_1) in this phase can be obtained as:

$$\min_{p_{UE-V}}(E_1) \triangleq (p_{UE-V} + p_c)T_{UE-V} \tag{7}$$

It is obvious that $E_1 << E_d$. However, for complete transmission of data, the following constraint should be satisfied by T_{UE_V}.

$$\int_0^{T_{UE-V}} B\log_2\left(1 + \frac{\omega p_{u-v}\,\varsigma}{\Psi^2 s_{UE-V}^{\alpha}}\right)dt = M \tag{8}$$

where, s_{UT-V} is a function of t and defined by: $s_{UE-V} = [h_{UE}^2 + (v.T_{UE-V} - v.t)^2]^{1/2}$.

4.2.2. Energy consumption in 2nd phase of the cellular-V2X mode

In this phase, each VUE transmits data to nearby VUE at each hop of entire multi-hop V2V transmissions. To send data destined to eNB, each VUE functions as a relay for receiving and transmitting the data unit. Hence, energy consumption (E_2) in this phase is the summation of energy consumed by each VUE of an individual hop. For simplicity, it is assumed that VUEs are equidistant (as they are moving with uniform velocity) and data transmission time is constant for VUE. Thus, E_2 can be calculated as:

$$\min_{p_{V\_V}}(E_2) \triangleq (n-1)(p_{V\_V} + p_c)T_{V\_V} \tag{9}$$

For guaranteed transmission of the message in $T_{V\text{-}V}$ interval at each hop of V2V transmission, the following constraint is satisfied by $T_{V\text{-}V}$, which is stated as:

$$\int_0^{T_{V-V}} B\log_2\left(1 + \frac{\omega p_{d-d}\,\varsigma}{\Psi^2\, r_{V-V}^{\alpha}}\right)dt \;=\; M \tag{10}$$

4.2.3. Energy consumption in 3rd phase of cellular-V2X mode

Like E_1 in Eq. (7), the energy consumption (E_3) in 3rd phase for uploading data unit to eNB by the VUE (in close proximity of eNB) of the entire multi-hop V2V transmission can be obtained as:

$$\min_{p_{V-eNB}}(E_3) \;\triangleq\; (p_{V-eNB} + p_c)T_{V\_eNB} \tag{11}$$

For complete transmission of the message to eNB, the transmission time (i.e., T_{V_eNB}) of the vehicle satisfies the following condition which is stated as:

$$\int_0^{T_{V-eNB}} B\log_2\left(1 + \frac{\omega p_{V-eNB}\,\varsigma}{\Psi^2 s_{V-eNB}^{\alpha}}\right)dt \;=\; M \tag{12}$$

where, $s_{V\text{-}eNB} = [h_{eNB}^2 + w^2 + (v.T_{V\text{-}eNB} - v.t)^2]^{1/2}$ is a function of t.

Combining Eq. (9), Eq. (11), and Eq. (13), total energy consumption in multi-hop cellular-V2X mode can be formulated as:-

$$\min\,(E_1 + E_2 + E_3) \le\; E_d \tag{13}$$

In eq. (13) also satisfies the constraints, $s_{UE\_V} \le d_{max}$ and $r_{V\text{-}V} \le d_{max}$.

To obtain optimized energy consumption in cellular-V2X mode, the following inequalities are also satisfied by In eq. (13), which are stated as:

$$s_{V-eNB} \le\; d_{max} \tag{13.1}$$

$$p_{UE-V} \le\; p_{max}, p_{V-V} \;\le\; p_{max}, p_{V-eNB} \le\; p_{max} \tag{13.2}$$

$$T_{UE-V} \;+ T_{V-V} + T_{V-eNB} \le D_{max} \tag{13.3}$$

4.3. Energy consumption in SCF mode

In SCF mode, UE transmits data unit to nearby VUE which is similar to *1st phase* of cellular-V2X mode. Unlike its *2nd phase*, the receiving VUE transmits data neither to adjacent VUE nor to eNB directly (in UL transmission). Instead, the receiving VUE stores the entire unit of data and carries it towards eNB. Thus, energy consumption in this phase of SCF mode is *zero*. Like *3rd phase* of cellular-V2X mode, the transceiver-VUE simply uploads the data unit to eNB in its close proximity and thus completes the entire transmission. Overall energy consumption in this mode depends on *1st* and *3rd phases* only. Therefore, using Eq. (7) and Eq. (11), total energy consumption in SCF mode is obtained as:

$$\min(E_1 + E_3) \leq E_d \tag{14}$$

where, In eq. (14) also satisfies the constraints (8) and (12).

4.4. Average transmission delay (UE-to-eNB)

Average respective transmission delays (D_1 and D_3) of *1st phase* and *3rd phase* of cellular-V2X and SCF modes are equal and can be computed as:

$$D_1 \leq \frac{M}{K(p_{UE-V})} \text{ and, } D_3 \leq \frac{M}{K(p_{V-eNB})} \tag{15}$$

Average respective transmission and transportation delay in *2nd phase* of cellular-V2X and SCF modes are calculated as:

$$D_2^{V2X} \leq (n-1) \times \frac{M}{K(p_{V-V})} \tag{16.1}$$

$$D_2^{SCF} \leq \frac{r_{UE-eNB}}{v} \tag{16.2}$$

Thus, average transmission delay from UE to eNB of direct, cellular-V2X and SCF modes can be formulated as:

$$T_{Direct} \leq \frac{M}{K(p_{UE-eNB})} \leq D_{max} \tag{17.1}$$

$$T_{V2X} = D_1 + D_2^{V2X} + D_3 \leq D_{max} \tag{17.2}$$

$$T_{SCF} = D_1 + D_2^{SCF} + D_3 \leq D_{max} \tag{17.3}$$

5. RESULT ANALYSIS

The goal of this section is to evaluate the performance of single-hop direct mode, multi-hop cellular-V2X mode, and SCF mode of UL data transmission in an LTE cell in terms of energy consumption and average transmission delay (from UE to eNB). To optimize the metrics (i.e., energy and transmission delay), we use the derived equations (of section 4) and parameter values of Table II (which are adopted from [7] and [17]) and carry out the (numerical and simulation) results. Based on optimized metrics value, we find out the best suitable mode of transmission for delay-sensitive applications.

Table II. Parameter Values

Parameter	Value	Parameter	Value
r	500-1000 m	p_c	100 mW
M (Mbit)	VoIP data: 0.5 - 3.0	v	72 Km/h
	Video data: 10 - 60	D_{max} (sec)	15 (VoIP), 20 (Video)
B	15 MHz	d_{max}	200 m
Ψ	-114 dBm/MHz	p_{max}	250 mW
α	3.75	h_{eNB}	30 m

ω	10^{-2}	h_{UE}	1.5 m
BER	10^{-6}	w	40 m

5.1. Simulation setup

Entire simulation is carried out in *ns-3*[1] version 3.0 over LTE module. Inside the LTE module, we use LTE-Lena and LTE-D2D[2] modules. To simulate the system model in LTE-V2X environment, we explore the programs of [18]-[19] as the base model of LTE-D2D communication, and its extension in [20] to support UE-to-Network relay operation. This includes D2D communication over sidelink (SL) application which only supports IPv6-based relaying feature in UE-to-Network. Data rate varies with the variation of transmission power, controlled by *LteUePhy::TxPower* of UE. For simplicity, we consider six moving nodes (as VUEs at an average speed 72 km/hr) in between UE and eNB where five nodes move in the direction of eNB and one node moves in the reverse direction which is a typical case, seen in a highway. The classes *LteUeRrc* and *LteSlUeRrc*[2] are responsible for creating and maintaining one-to-one direct communication via SL between every pair of UEs/VUEs. All intermediary nodes (i.e., VUEs) are connected through the SL for providing relay services using the object *ProseHelper* of the class *LteSideLinkHelper*[2].

To employ UDP applications, we set up UDP client-server model by adding *UdpClientHelpe*r and *UdpServerHelpe*r classes at UE and Remote UE respectively. We also provide required set of attributes values in the constructor such as server port number at UE etc. To send UDP-datagrams, the object of *ApplicationContainer* class always remains active at UE. The *SetAttribute* method of the class *UdpClientHelpe*r, sets maximum number of packets to be transmitted, packet intervals, and maximum packet size etc. To simulate the entire system model, we consider datagram size as 1024 bytes and packet interval as 1 msec. To support relay-assisted cellular-V2X mode, we run the simulator for 5 sec and 22 sec for sending 185 VoIP data packets and 3691 video data packets respectively, one after another from UE/VUEs to remote-UE.

5.2. Simulation and numerical results

Both simulation and numerical results are shown in *Figure 3, Figure 4, and Figure 5.* In all figures, the simulation results are slightly higher than numerical results. This bit of deviation is due to: *1.* there is an impact of signal strength in simulation results leading higher delay and more energy consumption. *2.* an inter packet delay is set to 1 msec in simulation which causes higher delay compared to numerical results. For SCF mode of all the figures, energy consumption and delay in the simulation and numerical results are almost same which noticeably differ in case of single-hop direct and multi-hop cellular-V2X modes. Table III, IV, and V explicitly show the detailed empirical results of three modes of transmissions for VoIP and video applications.

Table III. Overall Energy Consumption W.R.T. Messaze Size

Overall energy consumption for VoIP application				**Overall energy consumption for Video application**			
Message size (Mbit)	**Direct mode (mJ)**	**SCF mode (mJ)**	**V2X mode (mJ)**	**Message size (Mbit)**	**Direct mode (mJ)**	**SCF mode (mJ)**	**V2X mode (mJ)**
0.5	32.00	2.50	19.04	10.00	600.00	50.00	385.00
1.0	66.89	5.00	38.49	20.00	1200.00	100.00	769.00
1.5	100.34	7.50	57.93	30.00	1800.00	150.00	1158.00

[1] https://www.nsnam.org/

[2] https://github.com/usnistgov/psc-ns3/blob/psc-4.0/src/lte/examples/d2d-examples/lte-sl-in-covrg-relay-building.cc

2.0	134.89	10.00	76.98	40.00	2400.00	200.00	1543.00
2.5	169.00	12.50	96.42	50.00	3000.00	250.00	1928.00
3.0	197.00	15.10	115.87	60.00	3600.00	300.00	2313.00

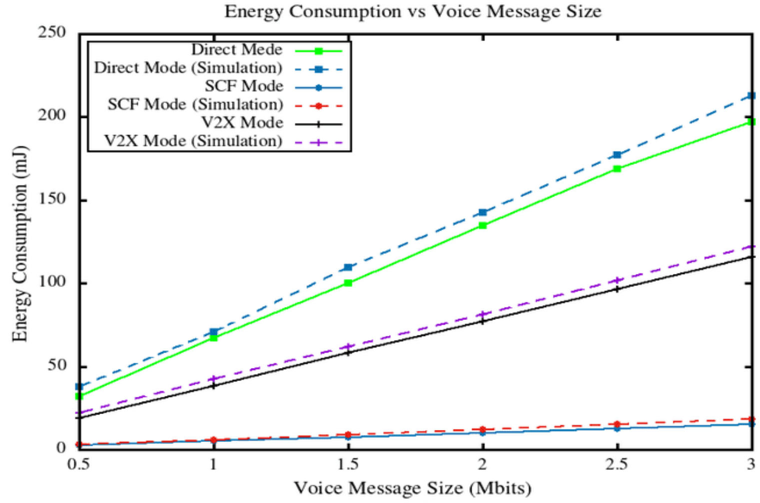
Table IV. Overall Energy Consumption W.R.T. Cell Radius

Overall energy consumption for VoIP application				**Overall energy consumption for Video application**			
Cell radius (m)	**Direct mode (mJ)**	**SCF mode (mJ)**	**V2X mode (mJ)**	**Cell radius (m)**	**Direct mode (mJ)**	**SCF mode (mJ)**	**V2X mode (mJ)**
500	90.00	7.50	57.93	500	1800.00	150.00	1158.00
600	180.00	7.50	59.27	600	3600.00	150.00	1189.00
700	321.00	7.50	61.95	700	6300.00	150.00	1243.00
800	---	7.50	64.00	800	---	150.00	1287.00
900	---	7.50	70.90	900	---	150.00	1423.00
1000	---	7.50	74.69	1000	---	150.00	1498.00

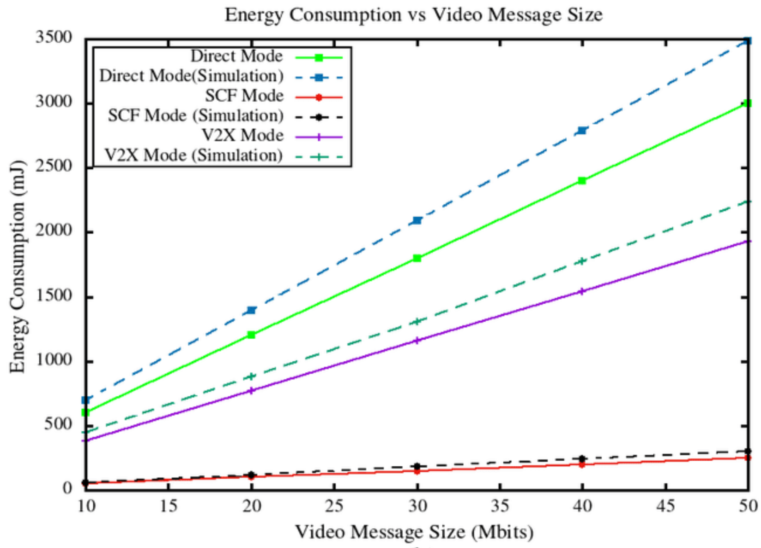
Table V. Overall Transmission Delay W.R.T. Cell Radius

Overall transmission delay for VoIP application				**Overall transmission delay for Video application**			
Cell radius (m)	**Direct mode (sec)**	**SCF mode (sec)**	**V2X mode (sec)**	**Cell radius (m)**	**Direct mode (sec)**	**SCF mode (sec)**	**V2X mode (sec)**
500	0.30	25.075	0.189	500	6.00	26.50	11.50
600	0.60	30.075	0.382	600	13.00	31.50	11.78
700	1.07	35.075	0.575	700	23.42	36.05	12.26
800	---	40.075	0.764	800	---	41.05	12.50
900	---	45.075	0.957	900	---	46.05	13.30
1000	---	50.075	1.150	1000	---	51.05	13.62

Figure 3 demonstrates the total energy consumptions in three modes with the fixed cell radius, 500 m and 6 vehicles. It is clearly seen that energy consumption increases gradually with the increase of message size. Being at the cell edge, UE transmits data to eNB and covers a long distance and thus energy consumption is achieved the maximum in single-hop direct mode of transmission. In relay-assisted multi-hop cellular-V2X mode, energy consumption depends not only on UE but also relay-assisted VUEs moving towards eNB. As a result, cellular-V2X mode is always comparable than other two modes. On the other hand, SCF mode internally uses V2X transmission in first and last hops of its entire path of communication with transmission & transportation. Since energy consumption in the intermediary hops of SCF mode is *zero* as transmission is entirely stopped in this phase for carrying data, the overall energy consumption reaches to minimum. Though SCF mode is most energy efficient, but delay sensitive applications suffer a lot in this mode for its transportation phase.



(a)



(b)

Figure 3. Energy consumption w.r.t. (a) VoIP data size, and (b) video data size for r = 500 m and n = 6

Performance of three modes transmissions in terms of energy consumption w.r.t. varying cell radius are compared in *Figure 4*. It is clearly seen that, overall energy consumption increases exponentially in direct mode, almost linearly in cellular-V2X mode, and remains constant in SCF mode with the increase of cell radius for respective average data size of VoIP and video applications. Being at the cell edge and covering long distance, the channel gain between UE and eNB reduces significantly, which results more transmission power and longer transmission time in direct mode. In this mode, UE transmits data with its full battery power (i.e., 250 mW) at the cell radius 500 m, and entire transmission stops at cell radius 700 m which is due to fully exhausted battery power. In contrary, least power and least transmission delay are incurred at each hop of V2V mode which results overall significant performance. On the other hand, total energy consumption of SCF mode depends only on 1st and 3rd phases and thus, it is independent of cell radius. As a consequence, SCF mode is most advantageous only in term of energy consumption for large cell radius.

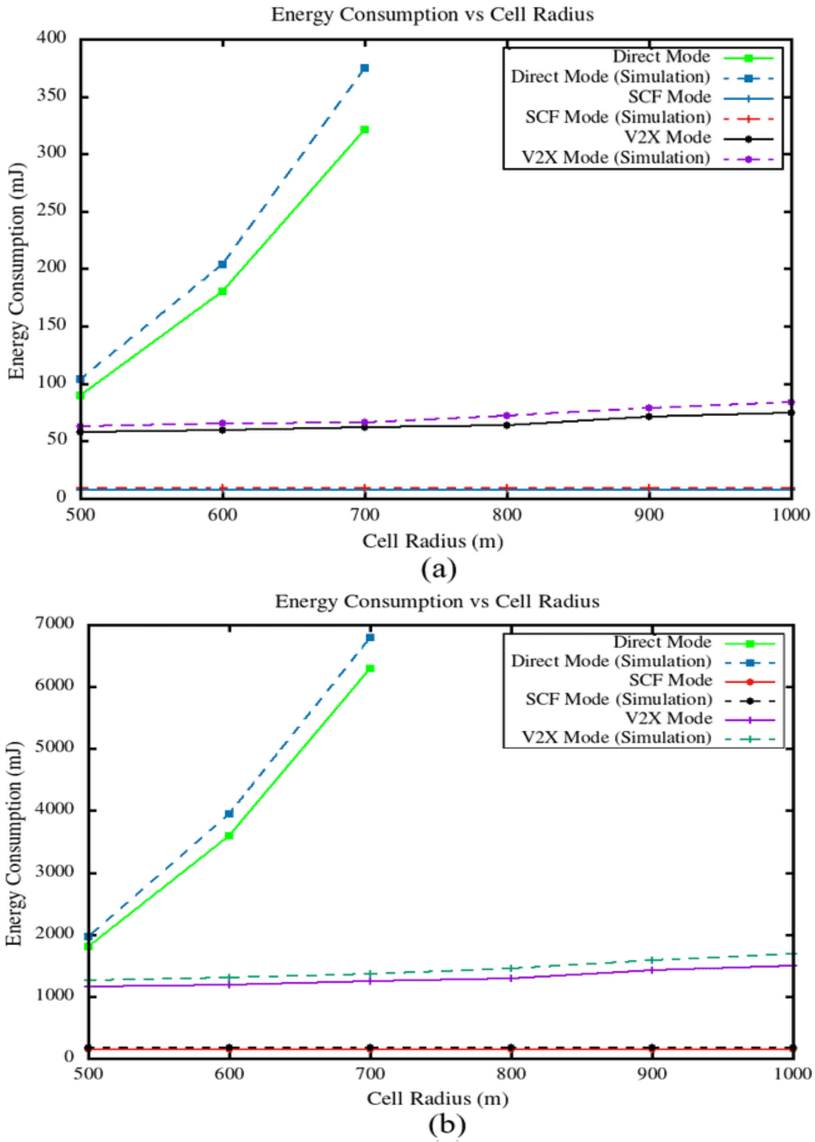


Figure 4. Energy consumption w.r.t. cell radius, where (a) average VoIP data size = 1.5 Mb and (b) average video data size = 30 Mb with n = 6

Figure 5, shows the effect of cell radius on average transmission delay (from UE to eNB) of three modes for average respective data sizes (of VoIP and video applications). Transmission delay has a significant impact on delay-sensitive applications. Due to huge delay incurred by SCF mode, none of the real-time applications run smoothly. On the other hand, average transmission delays of single-hop direct and multi-hop cellular-V2X mode are always considerable (with delay thresholds 15 sec for VoIP, and 20 sec for video applications with their respective acceptable data rates). Irrespective type of applications, transmission delay of direct mode is much better than cellular-V2X mode within cell radius 600 m, which is more prominent for video application (in *Fig. 4(b)*). In direct mode, the entire transmission stops at the cell radius 700 m onwards as the battery power is full exhausted, which cripples the applications running at the ends. This is due to the maximum power allocation of UE for achieving high data rate. However, average transmission delay of cellular-V2X mode always outperforms than direct mode beyond 600 m cell radius. This is because of total power allocation of 6 VUEs (in our experiment) is greater than maximum power of UE in direct mode. Thus, cellular-V2X mode is the best suitable transmission mode, optimizing both overall energy and overall transmission delay for all delay sensitive real time applications than other two because this mode exploits the relaying and mobility features of VUEs.

From *Figure 3*, *Figure 4*, and *Figure 5*, the following points are derived:

- Delay sensitive applications seamlessly run in direct mode satisfying conditions: cell radius < 700 m and transmission delay $\leq D_{max}$ (which is application specific constraint).
- SCF mode of transmission should be avoided for the applications with the requirement of (soft) guaranteed latency.
- Relying-based multi-hop cellular V2X mode is proved to be provided services requiring accessibility, latency and throughput with sustainable energy consumption.

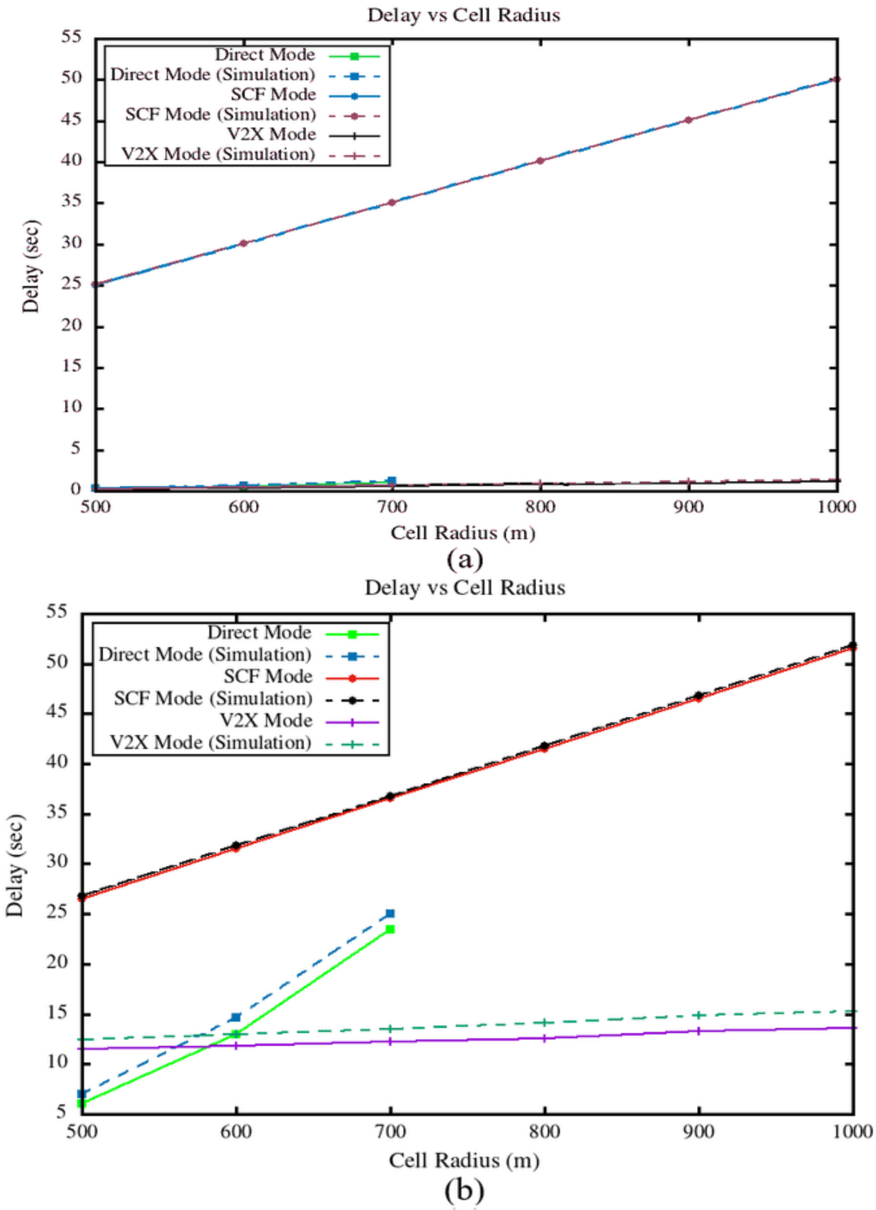


Figure 5. Average transmission delay (from UE to eNB) w.r.t. cell radius where $M_{avg.(VoIP)}$ = 1.5 Mb, avg. $M_{avg.(Video)}$ = 30 Mb, $D_{max(VoIP)}$ = 15 sec, $D_{max(Video)}$ = 20 sec with n = 6

6. CONCLUSIONS

In this article, we consider relaying-based cellular-V2X enabled delay-sensitive model to achieve energy-saving and low latency communication while UE transmits data from the cell edge. Satisfying the system model, we formulate the problem for direct, cellular-V2X, and SCF mode of transmissions with the guaranteed delay constraints of various delay sensitive applications. Numerical results validated by *ns-3*, demonstrate that direct mode always consumes maximum energy with the considerable delay, whereas least energy with maximum delay (beyond the threshold) is always incurred in SCF mode. On contrary, cellular-V2X mode requires moderate energy and minimum delay. Though there is always a trade-of between energy consumption and delay, the multi-hop cellular-V2X mode is most preferable for Public Safety Networks (PSNs) due to its moderate power with satisfactory energy-saving-low-delay requirement. Thus, the relay-assisted cellular-V2X mode is exhaustively used in UL data transmission for real-time applications of PSN.

7. FUTURE WORKS

The system model (used in this article) may be further enhanced to support highway scenarios in rural as well as urban areas for analyzing the impact of relay-based LTE-V2X/5G-NR-V2X networks for various services provided by transport protocols. Some optimal and/or opportunistic transmission modes may also be included for providing better services.

CONFLICT OF INTEREST

Authors of the paper declare no conflict of interest in all respects.

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REFERENCES

[1] K. Nasim and T. J. Hall, "Techniques for Offloading LTE Evolved Packet Core Traffic Using Openflow : A Comparative Survey & Design Reference," International Journal of Computer Networks & Communications (IJCNC), vol. 11, no. 1, pp. 109-125, Jan. 2019.

[2] N. N. Sirhan, G. L. Heileman, C. C. Lamb, "TRAFFIC OFFLOADING IMPACT ON THE PERFORMANCE OF CHANNEL-AWARE/QOS-AWARE SCHEDULING ALGORITHMS FOR VIDEO-APPLICATIONS OVER LTE-A HETNETS USING CARRIER AGGREGATION," International Journal of Computer Networks & Communications (IJCNC), vol. 7, no. 3, pp. 75-90, May 2015.

[3] P. Kundu, M. K. Rana, B. Sardar, and D. Saha, "Finding Practicable Nesting Level in Multi-level Nested Mobile Networks," in proc. of 2019 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), pp. 1-6, Dec. 2019.

[4] P. Kundu, M. Mahata, M. K. Rana, and B. Sardar, "Improving Spectral Efficiency for Device-to-Device Data Offloading in Underlay Cellular Networks," in proc. of 3rd IEEE Conference on Information and Communication Technology, pp. 1-6, Dec. 2019.

[5] M.Saimler, and S.C. Ergen, "Power Efficient Communication Interface Selection in Cellular Vehicle to Everything Networks," in proc. of 2019 IEEE Wireless Communications and Networking Conference (WCNC), pp. 1-6, Oct. 2019.

[6] U. Demir, C. Toker and Ö. Ekici, "Energy-Efficient Deployment of UAV in V2X Network Considering Latency and Backhaul Issues," in proc. of 2020 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), 2020, pp. 1-6, May 2020.

[7] C. Zheng, D. Feng, S. Zhang, X. Xia, G. Qian, and G. Y. Li, "V2X-Enabled Energy-Efficient Transmission in Cellular Networks," 2018 10th International Conference on Wireless Communications and Signal Processing (WCSP), pp. 1-6, Oct. 2018.

[8] M. B. Brahim, Z. H. Mir, W. Znaidi, F. Filali, and N. Hamdi, “QoS aware video transmission over hybrid wireless network for connected vehicles,” IEEE Access, vol. 5, pp. 8313–8323, June 2017.

[9] S. E. Li, S. Xu, X. Huang, B. Cheng, and H. Peng, “Eco-departure of connected vehicles with V2X communication at signalized intersections,” IEEE Trans. Veh. Technology, vol. 64, no. 12, pp. 5439–5449, Dec. 2015.

[10] L. Le, A. Festag, R. Baldessari, and W. Zhang, “Vehicular wireless short range communication for improving intersection safety,” IEEE Communication Mag., vol. 47, no. 11, pp. 104–110, Nov. 2009.

[11] B. Di, L. Song, Y. Li, and G. Y. Li, “Non-orthogonal multiple access for high-reliable and low-latency V2X communications in 5G systems,” IEEE J. Select. Areas Communication, vol. 35, no. 10, pp. 2383–2397, Oct. 2017.

[12] A. Masmoudi, S. Feki, K. Mnif, and F. Zarai, “A mixed traffic sharing and resource allocation for V2X communication,” in proc. of Int. Conf. EBus. Telecommunication New York, NY, USA: Springer, pp. 219–233, Nov. 2019.

[13] B. Coll-Perales, J. Gozalvez, and V. Friderikos, “Energy-efficient opportunistic forwarding in multi-hop cellular networks using device-to-device communication” in Emerging Telecommunication Technologies,” in Transactions on Emerging Telecommunications Technologies, vol. 27 , no. 2 , pp. 249-265, Feb. 2016.

[14] P. Kolios, V. Friderikos, and K. Papadaki, "Ultra Low Energy Store-Carry and Forward Relaying within the Cell," 2009 IEEE 70th Vehicular Technology Conference Fall, pp. 1-5, Sep. 2009.

[15] B. Coll-Perales, J. Gozalvez, and V. Friderikos, "Opportunistic networking for improving the energy efficiency of multi-hop cellular networks," in proc. of 2014 IEEE 11th Consumer Communications and Networking Conference (CCNC), pp. 569-574, Jan. 2014.

[16] Y. Lmoumen, Y. Ruichek, and R. Touahni,"A Cooperative Approach to Extend Cellular Coverage via D2D Architecture based on OLSR Protocol," International Journal of Computer Networks & Communications (IJCNC), vol. 12, no. 5, pp. 81-96, Sept. 2020.

[17] C. Zheng, D. Feng, S. Zhang, X. Xia, G. Qian, and G. Y. Li, "Energy Efficient V2X-Enabled Communications in Cellular Networks," in IEEE Transactions on Vehicular Technology, vol. 68, no. 1, pp. 554-564, Jan. 2019.

[18] R. Rouil, F.J. Cintrón, A. Ben Mosbah, and S. Gamboa, “An LTE Device-to-Device module for *ns-3*”, in proc. of the Workshop on *ns-3*, 15-16 June 2016, Seattle (Washington).

[19] R. Rouil, F.J. Cintrón, A. Ben Mosbah, and S. Gamboa, “Implementation and Validation of an LTE-D2D Model for *ns-3*”, in proc. of the Workshop on *ns-3*, 13-14 June 2017, Porto (Portugal).

[20] Gamboa, S., Thanigaivel, R. and Rouil, R., “System Level Evaluation of UE-to-Network Relays in D2D enabled LTE Networks”, in proc. 2019 IEEE 24th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks, September 2019, Limassol (Cyprus).

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