

D2D in LTE vehicular networking: system model and upper bound performance

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Abstract—The Device-to-Device (D2D) communication over the Long Term Evolution (LTE) cellular system is emerging as a key technology to support safety and traffic efficiency applications in Vehicular Ad-hoc NETWORKS (VANETs). By offering a flexible usage of the radio interface, it allows vehicles to directly communicate each other, while experiencing low-latency and highly reliable data delivery. Anyway, the impact that application traffic patterns and transmission settings have on the overall performance is still unclear and in this context it is necessary a deep study for driving future research activities. To this end, the present contribution proposes a flexible methodology that characterizes, from a system level point of view, the upper bound performance of vehicular D2D communications as a function of the application, the access layer settings, and the channel behavior. Model outcomes have been used to provide insights about the most suitable transmission parameters, the achievable transmission range, and the supported vehicles density in VANETs scenarios.

I. INTRODUCTION

Vehicular Ad-hoc NETWORKS (VANETs) are considered by the scientific community as one of the most valuable means to improve road safety and transport efficiency. In fact, Vehicle-to-vehicle (V2V) communications let vehicles in close proximity to communicate and cooperate each other for being aware of the local surrounding and for distributing warning messages in case of critical traffic situations [1].

At the time of this writing, the IEEE 802.11p specification [2] represents the *de facto* standard for vehicular networking. However, by relying on a distributed channel access scheme, it poorly scales with the network load, thus it is unsuitable in scenarios where cooperative safety applications bring to massive, frequent, and periodic broadcast transmissions. More recently, instead, the Device-to-Device (D2D) communication using the Long Term Evolution (LTE) cellular system is emerging as a key technology to support V2V applications. D2D enables a *direct* communication among vehicles, bypassing the cellular infrastructure [3]. Moreover, the *localized* and *ad hoc nature* of D2D communications promises to well guarantee the ultra-low latency and reliability requirements of cooperative vehicular safety applications [4].

In line with these premises, several works (among which [5]-[7] and many more) have already investigated radio resource management issues in heterogeneous environments, where both D2D and traditional cellular communications co-exist. In order to better satisfy the requirements of emerging safety-critical applications in vehicular networks, other contributions started to evaluate the feasibility to allocate a dedicated

LTE spectrum to V2V communications [8][9]. What however remains surprising is that, at the time of writing and to the best of authors' knowledge, the impact of application traffic patterns and transmission settings on the overall performance is still unclear and a deep study needs to be addressed for driving future research activities in this area.

To bridge this gap, this paper proposes a flexible methodology that characterizes vehicular D2D communications as a function of the application traffic pattern (i.e., packet size and message generation rate), the access layer settings (i.e., transmission power, Modulation and Coding Scheme, operative bandwidth), and channel behavior (i.e., propagation model). The contribution of the developed model is twofold: (i) it can be used for evaluating the amount of physical resources needed to accommodate the traffic generated by safety-critical applications; (ii) it provides important insights about the most suitable transmission parameters and the vehicles density supported under specific application and topology requirements. Furthermore, our findings are also valid in the 5G context where vehicular D2D communications are identified as one of the most important use cases enabled by a specific *5G network slice* as discussed in [10].

The remainder of the paper is organized as follows. A background on the D2D technology and its adoption in V2V communications, is illustrated in Section II. The devised system model and its exploitation on the analysis of real use cases are discussed in Section III and Section IV, respectively. Finally, Section V concludes the paper.

II. BACKGROUND AND MOTIVATIONS

D2D communication is a radio technology that enables two devices to communicate directly without the usage of the network infrastructure. This new solution gains momentum for the promising benefits in term of high data rate, low latency, and energy consumption. In fact, telco operators started to consider this technology as a key requirement for the current (i.e., 4G) and future cellular systems (i.e., 5G). As a result, D2D communications have been partially introduced in 3rd Generation Partnership Project (3GPP) Rel. 12 under the name of *Proximity Services* (ProSe) [11] and are expected to be fully standardized in the next 3GPP Rel. 13.

Basically, D2D communications can be classified as *out-band* and *in-band* according to the radio spectrum utilization. The former category assumes that the D2D links exploit unlicensed spectrum. The motivation behind this choice is

to eliminate the interference among cellular and D2D transmissions [12]. The latter category, instead, proposes to use the cellular spectrum (licensed band) for both D2D and cellular transmissions. The motivation for such an approach is the high control of the cellular infrastructure regarding the radio spectrum; in this case, it is assumed that the intercell interference can be mitigated by managing efficiently the radio resources.

Inband D2D can improve the spectral efficiency of the network by reusing the same cellular radio spectrum (i.e., *underlay* mode) or by assigning a dedicated portion of cellular resources to D2D users (i.e., *overlay*) [13], [14], [15]. Naturally, even if dividing the cellular spectrum between cellular and D2D links avoids interference phenomena, intercell interference is a key issue in underlaying D2D communications and has to be taken into account.

A. D2D for Vehicular Networking

Vehicular safety applications rely on the exchange of messages among nearby vehicles sharing their kinematics and position information to build an augmented perception of the surrounding environment. According to the European Telecommunications Standard Institute (ETSI) standards [16], such messages, typically referred to as Cooperative Awareness Message (CAM), are frequently sent in broadcast in the one-hop neighborhood of a vehicle.

Recently, the research community started to investigate the ability of LTE to support cooperative safety applications [17] due to its high capacity, high data rate, and nearly ubiquitous coverage; preliminary results are reported in [18]. The delivery of CAMs on LTE requires two hops: from the vehicle to the evolved NodeB (eNB) and from the eNB to vehicles, either in unicast or multicast/broadcast manner. This would result in a high latency and high capacity demands in the uplink direction to accommodate the *frequent* delivery of packets by several vehicles, paving the way for D2D as enabler of V2V communications [3], [4], [19]. Motivations are as follows:

- D2D allows to manage *direct communications among devices* that are in proximity without passing from the eNB, which well suits to the localized nature of V2V.
- The *hop gain* achieved in bypassing the eNB can address the latency requirements of V2V safety applications.
- The *proximity gain* allows to enjoy higher data rate, translating in increased reliability, crucial for safety-critical data, and lower power consumption for vehicular devices, if they are battery-powered.
- Unlike 802.11p expected to be introduced only in newly sold cars, the use of D2D on LTE would extend the horizon of vehicles to all traffic participants, also pedestrians, cyclists, motocyclists as long as equipped with their smartphones.

Some literature solutions rely on underlay approaches [5], [6], while other assume a dedicated spectrum for D2D communications [9]. In the former cases, Radio Resource Management (RRM) schemes, which decide *how to allocate* (in a centralized or distributed fashion) *which resources* to cellular

and D2D links, play a crucial role for the success of D2D and need to be re-engineered in vehicular environments compared to conventional cellular systems due to their unique features.

The usage of uplink resources for D2D is preferred: (i) since they are typically underutilized in the cellular spectrum (such a trend is expected to change with the ever increasing machine-type communications), and (ii) since it only causes interference to the eNB.

Overall, the literature is still at its infancy, several questions need to be answered to analyze the opportunities of D2D for vehicular safety applications and to get insight into the scalability and effectiveness of such an approach, e.g., which is the maximum range of communications for D2D V2V links (the majority of works statically set it, e.g., around 20 m [5], [6]), which are the number of required resources to accommodate vehicular application demands and the number of supported vehicles. In this paper, we aim at filling this gap, by providing preliminary answers to those questions.

III. SYSTEM MODEL

In this section, we present a system level model that characterizes D2D communications enabled through the LTE technology. By taking into account the application traffic patterns, access layer settings, and the channel behavior, different system metrics can be easily estimated, like the maximum transmission distance that can be reached with a specific Modulation and Coding Scheme (MCS), the number of physical resources needed to transmit application packets, and the upper bounds of the supported node density.

Once some specific system parameters are known a priori (e.g., transmission power, packet size and generation rate, bandwidth, MCS, and so on), the proposed model provides an easy and immediate way to capture the performance of the communication among vehicles. Moreover, it can also be adopted for sizing and configuring D2D communications under a specific set of constraints (covering, for example, the target transmission range, the available bandwidth, and so on).

As shown in Figure 1, the proposed model fully integrates the most important facets belonging to the LTE radio interface at both PHY and MAC layers, that are: physical settings, Adaptive Modulation and Coding (AMC) module, and propagation losses. In particular, it receives in input a set of mandatory and optional parameters. The former ones identify system details, like operative bandwidth, transmission power, and application settings. Optionally, a target transmission range, which affects the supported device density, can be considered to suggest suitable physical settings and derive node density supported in VANETs.

Assumptions, models, and methodologies characterizing the proposed approach are presented in the following. For the sake of clarity, a summary of all the adopted symbols is reported in Table I.

A. Assumptions

The reported analysis can be applied to different D2D communications use cases. Indeed, it generates results under

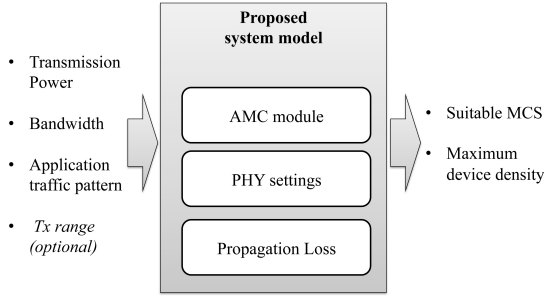


Fig. 1. The proposed model: relation among input and output variables.

TABLE I
LIST OF NOTATIONS.

Parameter	Description
N_v	Number of vehicles [#]
S_m	CAM size [bits]
A_r	CAM generation rate [packets/s]
ΔT	Observation time window [s]
B	Operative bandwidth [Hz]
Δf	Sub-channel size in the frequency domain [Hz]
T_{tti}	Time slot duration [s]
N_r^{tti}	Number of radio resources available in a single time slot [#]
N_{tti}	Number of time slots available in ΔT [#]
N_r	Total number of resources available in ΔT [#]
P_{tx}	Transmission power [W]
$N_{r,tx}$	Number of resources used for the transmission [#]
$\gamma(P_{tx}, N_{r,tx})$	Signal to Noise Ratio experienced by a possible destination node [dB]
P_N	Noise power [dB]
L	Total propagation loss [dB]
L_{pnl}	Penetration loss [dB]
L_{ptl}	Path loss [dB]
d	Distance between sender and receiver [m]
S_{tbs}	Transport Block Size [bits]
$N_{r,tx}^{req}$	Number of resources required for transmitting application packets in ΔT [#]
d_{max}	Maximum transmission range [m]
$V_{density}$	Maximum vehicle density [messages/m]
M_{cs}	Modulation and coding scheme [#]

a wide range of settings and conditions, that satisfy some assumptions presented below.

The reference scenario for our study foresees vehicular devices in a given area that periodically generate CAMs, broadcasted using D2D links through the LTE wireless communication interface. Without loss of generality, it is supposed that all vehicles generate CAMs of the same size, S_m , and with the same generation rate, A_r . Further settings can be easily accommodated.

An *inband overlay mode* is considered as a reference for building up D2D communications. As a consequence, vehicles use a dedicated portion of the spectrum, B , not overlapped with frequencies allocated to cellular communications. Of course, the system model can be easily extended for considering more complex scenarios where interfering signals negatively influence the quality of communication links.

In such a case, the aim is to obtain an *upper bound* performance of D2D communications over LTE systems. It

is assumed that vehicles transmit packets in a completely *interference-free* manner: resources used by a given device are not concurrently selected by any other node within its transmission range. Note that once the transmission settings have been chosen (think for example to the transmission power and the bandwidth), the coverage area of each device is quite defined too. All the devices use the same transmission power, P_{tx} and the same MCS index, hence they have the same transmission range. Furthermore, devices implement a simple Single-Input and Single-Output (SISO) transmission scheme.

B. Physical model

LTE radio resources are allocated in a time/frequency domain. In the time domain, they are distributed every Transmission Time Interval (TTI), each one lasting 1 ms. In the frequency domain, instead, the whole bandwidth is divided into sub-channels with size $\Delta f = 180$ kHz. As known, in LTE a time/frequency radio resource, i.e., the smallest radio resource that can be used for data transmission, is called Resource Block (RB).

We consider to observe the behavior of D2D communications during a relatively large time interval ΔT . In such a case, the number of consecutive time slots available in ΔT is equal to $N_{tti} = \Delta T / T_{tti}$. The transmission bandwidth is 90% of the channel bandwidth B . Hence, the amount of RBs available in each time slot is equal to $N_r^{tti} = 0.9(B/\Delta f)$. In addition, the total number of available resources in the considered observation time interval ΔT is:

$$N_r = N_r^{tti} N_{tti} = 0.9 \frac{\Delta T B}{T_{tti} \Delta f}. \quad (1)$$

Now, N_r represents just the number of resources that can be distributed among vehicles within a given coverage area during ΔT . However, the number of resources that each device should effectively use for transmitting a single application message depends on the packet size, the transmission power, and the MCS index. This aspect will be described in more details in the next sub sections.

C. Propagation model

The Signal to Noise Ratio (SNR) describes the signal degradation due to both propagation phenomena and noise. Its value is strictly influenced by the total transmission power, P_{tx} , the number of used resources, $N_{r,tx}$, the distance between source and destination, d , the noise power, P_N , and the total propagation loss L . It can be computed as follows:

$$\gamma(N_{r,tx}, d)|_{dB} = 10 \log_{10} (P_{tx}/N_{r,tx}) - L - P_N. \quad (2)$$

Note that the reported SNR has been obtained by assuming that the total power P_{tx} is uniformly distributed over the set of resources used for the physical transmission $N_{r,tx}$. The noise power P_N is assumed to be equal to -174 dBm for each sub channel Δf [20].

The propagation loss L is affected by different kinds of phenomena such as path loss, penetration loss, shadowing, and fast fading effects due to the signal multipath. Fast fading

and shadowing are generally modeled as random variables with 0 mean. Therefore, their impact on upper bounds of system performance can be neglected. Differently, penetration loss L_{pnl} and path loss L_{ptl} significantly influence the signal degradation. In line with [21], the penetration loss L_{pnl} is set to 10 dB. For D2D communications, the path loss is modeled through the following logarithmic equation: $L_{ptl} = 148 + 40 \log_{10}(d)$, where d is the distance between source and destination in kilometers. Accordingly, the total propagation loss L can be expressed as [14]:

$$L = L_{pnl} + L_{ptl} = 10 + 148 + 40 \log_{10}(d). \quad (3)$$

D. Adaptive Modulation and Coding model

The AMC module is integrated at the MAC layer for implementing the link adaptation. Hence, it can be used for mapping SNR values to MCS indexes, i.e., M_{cs} . Formally, we can describe the mapping function as

$$M_{cs} = \phi(\gamma(N_{r,tx}, d)). \quad (4)$$

Nevertheless, the relation between the SNR and MCS scheme is not defined through a closed mathematical relation. But, the mapping function is solved through pre-computed Block Error Rate (BLER) curves. In line with [20], which considers a target BLER of 10%, the mapping function integrated into the proposed model is reported in Figure 2. From the Figure, it is possible to observe that the higher is the SNR, the higher is the MCS scheme that can be used for the transmission. As expected, in fact, as soon as the signal quality increases, less robust and high speed modulation and coding techniques could be adopted, still guaranteeing an error probability lower than the target one.

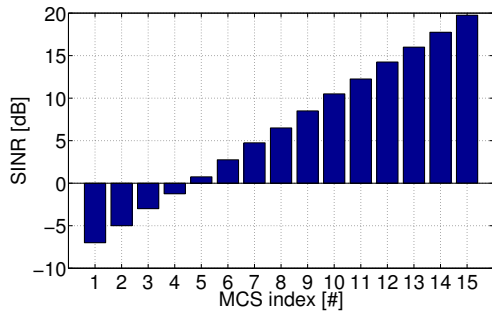


Fig. 2. Mapping function between SNR values and MCS indexes.

Let $\phi^{-1}(M_{cs})$ be the inverse function of Eq. (4). Hence, given the results reported in Figure 2 and the channel model described in the previous sub-section, it is possible to evaluate the maximum transmission range, d_{max} , as a function of the total transmission power, the selected MCS scheme, and the number of radio resources used for the physical transmission:

$$d_{max} = 10^{\frac{\phi^{-1}(M_{cs}) - 10 \log_{10}\left(\frac{P_{tx}}{N_{r,tx}}\right) + 10 + 148 + P_N}{40}}. \quad (5)$$

Just to provide an example, Figure 3 shows that the communication range decreases with the amount of bandwidth used

for the transmission due to the lower power level allocated to each sub channel. Moreover, lower MCS schemes, that correspond to more robust modulation and coding techniques, can ensure higher transmission ranges. Obviously, higher transmission ranges can be achieved by increasing the total transmission power.

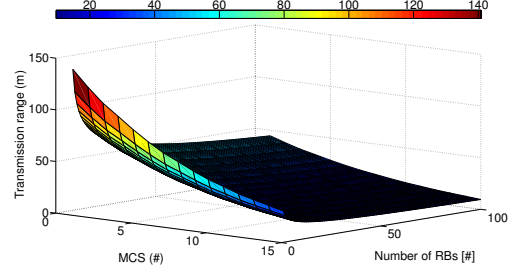


Fig. 3. Maximum transmission range for $P_{tx} = -2$ dBm.

In LTE systems, the Transport Block Size (TBS), S_{tbs} , is the number of bits that a flow can transmit in one or more sub-channels at the MAC layer (including MAC overhead and cyclic redundancy check trailer) during one TTI. Also in this case, we can formally define S_{tbs} as a function of both MCS and number of sub-channels used for the transmission:

$$S_{tbs} = \psi(M_{cs}, N_{r,tx}). \quad (6)$$

The $\psi(\cdot)$ function in LTE system is typically implemented by lookup tables. As reported in Figure 4, S_{tbs} depends on the MCS chosen by the AMC module, the number of physical resources selected for the transmission, and other physical settings (e.g., the number of antenna ports, the duration of the prefix code used at physical layer, and the number of symbols used by the control channel).

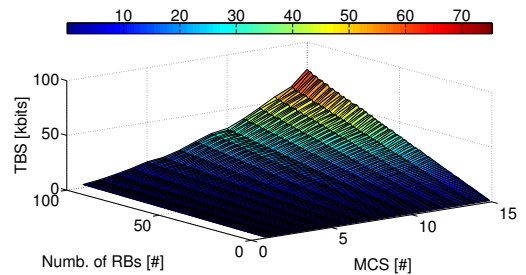


Fig. 4. Transport Block Size as a function of both MCS and number of sub-channels used for the transmission.

E. Sizing methodology

Now, Equations derived above can be used for estimating interesting performance indexes that characterize vehicular communications under different system settings.

First of all, known the application traffic pattern (the packet size S_m , the message generation rate A_r), and the Transport Block Size S_{tbs} , it is possible to compute the amount of

needed resources for each vehicular device to transmit a CAM generated in ΔT , when a specific MCS scheme is selected:

$$N_{r,tx}^{req} = \Delta T A_r S_m / S_{tbs}. \quad (7)$$

Without loss of generality, Eq. (5) can be simplified imposing $\Delta T = 1/A_r$. That is, $N_{r,tx}^{req}$ is just the ratio S_m/S_{tbs} .

Results in Figure 5 show that, as expected, larger CAMs bring to higher bandwidth consumption. Anyway, when the MCS scheme increases, the number of physical resources needed for transmitting a single packet decreases: higher MCS indexes, in fact, allow to transmit more bits within the single RB.

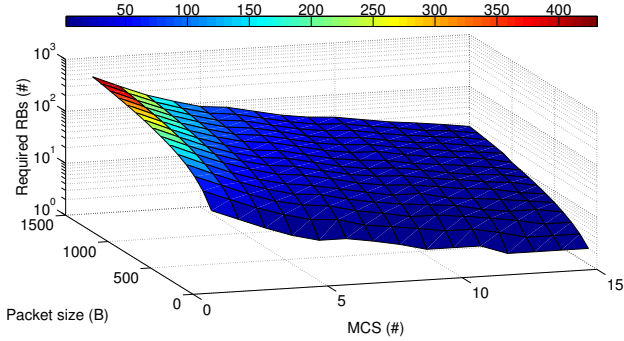


Fig. 5. Number of resources required for transmitting a single application message as a function of both message size and MCS scheme.

Finally, $N_{r,tx}^{req}$ and P_{tx} can be jointly considered to estimate the maximum physical transmission range d_{max} , as discussed in Section III-D. Hence, the vehicle density over a given lane [22] can be expressed as:

$$V_{density} = \frac{N_v}{2d_{max}} = \frac{N_r / N_{r,tx}^{req}}{2d_{max}} \quad [vehicle/m]. \quad (8)$$

The maximum vehicle density as a function of physical settings and application traffic pattern parameters is reported in Figure 6. It is worthwhile to note that it increases with the MCS scheme and decreases with the application packet size. In the first case, higher MCS values translate to lower transmission ranges (see also Figure 3). As a consequence, more vehicles can share N_r resources within a lower coverage area, thus increasing the vehicle density. In the second case, instead, when the packet size increases, a lower number of devices can share available resources within a given coverage area, thus bringing to a reduction of the vehicle density.

IV. NUMERICAL RESULTS

To demonstrate a preliminary usage of the proposed model, we evaluated, through an ad hoc simulator, the most suitable MCS scheme to use in a D2D scenario and vehicle density supported when varying access and application-layer parameters. To this end, we vary S_m from 100 bytes to 1500 bytes [4] and set A_r to 10 messages/s and 20 messages/s [4], $B = 5$ MHz, P_{tx} to -2 dBm and 10 dBm [5][23], and $P_N = -174$ dBm [20].

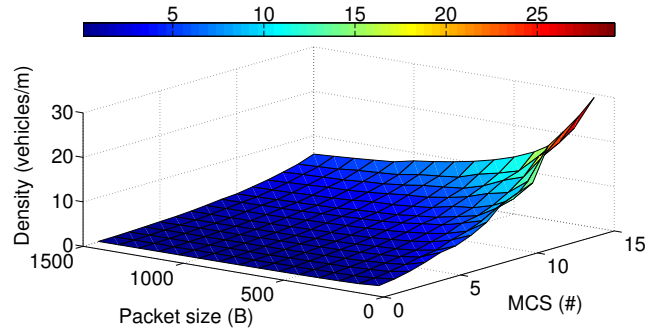


Fig. 6. Maximum vehicle density as a function of both MCS and packet size, for $P_{tx} = -2dBm$ and $\Delta T = 1/A_r = 0.1$ s

In addition to the discussion presented in the previous Section, results in Figure 7 show that to accommodate a larger packet size, a lower MCS index is required. When the packet size increases, in fact, more radio resources are used at the physical layer. In these conditions, the total transmission power is divided among more sub-channels, thus reaching lower SNR values at the target distance. Thus, in order to ensure the same error probability, a lower MCS scheme should be used.

Interestingly, by properly setting the MCS index and the transmission power, D2D links can be set-up over distances well suitable for the required *awareness range* in cooperative vehicular communications, in the order of around 100 m [1].

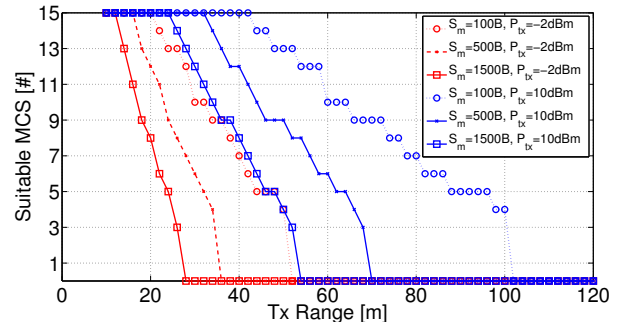


Fig. 7. Suitable MCS index vs. the target transmission range, when varying P_{tx} and S_m .

Physical settings and application traffic patterns are expected to significantly influence the number of vehicles that can communicate within a given coverage area. To this purpose, $V_{density}$ is reported in Figure 8, when setting the MCS index equal to the one ensuring the target transmission range (x-axis).

As expected, vehicle density decreases when the packet size and the message generation rate increase, since a lower number of transmissions can be accommodated. What it is important to notice is that achieved values are well above the typical vehicular density (in the order of 0.2 vehicle/m under highly congested scenarios in a single-lane road [22]).

This is true also under very challenging conditions in terms of application traffic patterns, i.e., $S_m=1500$ bytes, $A_r=20$

message/s, resembling a scenario where vehicles frequently exchange large messages to share the map of their surroundings in CAMs to allow cooperative maneuvers and, even, platooning [4].

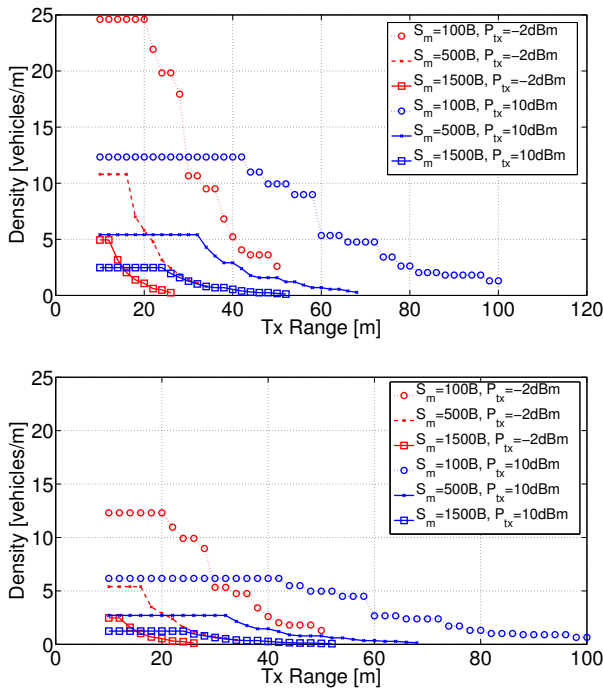


Fig. 8. Vehicle density vs. the target transmission range for (a) $A_r=10$ messages/s and (b) $A_r=20$ messages/s.

V. CONCLUSIONS

This paper presented a methodology that characterizes, from the system level point of view, D2D communications when applied to support cooperative vehicular applications. By considering PHY and MAC settings, application traffic patterns, and channel behavior, the model has been used to assess the number of radio resources needed to allow vehicles to broadcast their CAMs and the number of vehicles supported in a given area. Achieved upper bounds results show that D2D in LTE systems could really support the communication among vehicles, also under challenging requirements of cooperative applications. Moreover, the proposed model can be considered as a reference system performance to integrate in more realistic and complex studies and research activities in the context of vehicular networking. In the future, we plan to extend the proposed model in order to take into account more complex network and application settings and different physical transmission schemes, i.e., including Multiple input multiple output (MIMO). Moreover, simulation studies will be performed to evaluate the accuracy of the model.

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