On Coexistence of Vehicular Overlay Network and H2H Terminals on PRACH in LTE

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Abstract
Vehicular ad hoc networks (VANETs) that use IEEE 802.11p communication standard face a number of challenges, not least when it comes to safety messages on the VANET control channel (CCH) where short delay times and reliable delivery are of primary importance. In this paper we propose a vehicular machine-to-machine (VM2M) overlay network that uses Long Term Evolution (LTE) physical random access channel (PRACH) to emulate VANET CCH. The overlay network uses dedicated preambles to separate vehicular traffic from regular LTE traffic and a carrier sense multiple access with collision avoidance (CSMA-CA) layer similar to the one used in IEEE 802.15.4 to avoid the four step handshake and the overhead it incurs. The performance of the proposed overlay is evaluated under a wide range of PRACH parameters which conform to the scenarios with high vehicle velocities and large distances between roadside units (RSUs) that may be encountered in rural areas and on highways.

Keywords: vehicular ad hoc networks (VANETs); VANET control channel (CCH); 3GPP long term evolution (LTE); physical random access channel (PRACH); IEEE 802.15.4; human-to-human (H2H) traffic

1 Introduction

Vehicular ad hoc networks (VANETs) support a variety of applications like road safety, infotainment and telematics. In the Dedicated Short Range Communications (DSRC) framework, VANET communications use a control channel (CCH) for the exchange of safety messages, and one or more service channels (SCHs) for other purposes. Actual connection is implemented through a single- or multiple-antenna on-board unit (OBU) that supports communication with other vehicles as well as with roadside units (RSUs); the two types of communication are often referred to as vehicle to vehicle (V2V) and vehicle to infrastructure (V2I).

VANETs usually follows the DSRC standard which deploys the IEEE 802.11p standard for wireless communications [1], also referred to as Wireless Access for the Vehicular Environment (WAVE). IEEE 802.11p works well in urban areas with low to medium density vehicular population moving at low speeds and small inter-vehicle distances. However, available transmission rate will drop rapidly with the increase in distances between RSUs and OBUs and/or vehicle speeds [2]. Delays increase as well, due to the use of relatively small congestion windows and arbitration inter-frame spacing (AIFS) delays. In such cases, congestion and early saturation may easily result, esp. with a single-antenna OBU [3]. Spatial and communication capacity limitations of IEEE 802.11p were investigated in [4], and these problems were found to be aggravated in suburban and rural areas and on highways [5]. These problems are particularly noticeable when safety messages are concerned, as these are among the critical success factors for successful VANET deployment.

On account of those problems, there have been a number of proposals that use cellular network technology to implement a VANET, in particular the widely used Long Term Evolution (LTE) which meets most of the requirements for VANET applications. LTE provides high data rate, low latency (for new as well as handover calls), and reliable coverage over larger range of distances and speeds. In particular, it supports mobility and provides higher network capacity compared with IEEE 802.11p, as confirmed by a number of studies [5]–[8]. However, those studies found that the use of LTE solves only part of the problem. Namely, cellular networks are optimized for high performance mobile devices such as smartphones that connect human operators with one another as well as to internet-based servers. As the result, majority of human-to-human (H2H) traffic will flow in the downlink direction, i.e., from the base station (eNodeB, in case of LTE) towards the mobile terminal (MT); moreover, such traffic will predominantly consist of medium- to large-size flows. Both observations generally hold for infotainment and vehicular telematics flows on SCH [9].

On the other hand, traffic on the CCH, and safety messages in particular, have different properties. First, more likely than not, they originate at the vehicle, i.e., the OBU, meaning they will be sent in the uplink direction; and second, they will typically consist of short messages that need to be rapidly delivered and, possibly, broadcast back to other vehicles in the vicinity [10]. As the result, CCH traffic may easily lead to overload [11]. Another study has shown that IEEE 802.11p is more reliable for beacon messages broadcasts by vehicles, as they need not go through the LTE core network before being transmitted to other vehicles [8].

One of the unfortunate results of this difference is that most of the studies in vehicular networks have focused on a single type of applications, and the solutions obtained therein are by necessity partial [9]. A better solution would be to use heterogeneous vehicular networks with multiple radios and/or access technologies working in a collaborative manner. One representative solution that follows this approach is a hybrid network using both IEEE 802.11p and LTE, as has been proposed in [7]. The combination uses multi-hop clustering of IEEE 802.11p with LTE to achieve high data packet delivery ratio and low latency. Another integrated proposal was described in [12] with the goal of simplifying high speed inter-vehicle communications.

Previous comments notwithstanding, it may be possible to use LTE as a single access technology but with heterogeneous types of traffic—in particular, by adapting it to the characteristics of CCH traffic. The main culprit behind performance degradation for CCH traffic is the comparatively long and inefficient connection setup conducted through the four-step handshake on physical random access channel (PRACH) [13], [14]; this handshake must be simplified or even avoided, if performance is to be improved. Recently, a solution that eliminates the need for the four step handshake has been proposed [15]; while this proposal focuses on the rapidly expanding machine-to-machine (M2M) traffic [16], it can be applied equally well to VANETs by considering OBUs as hybrid devices that generate both SCH and CCH traffic with specific challenges due to high vehicle speed and high data rate.

In this proposal, regular (SCH) traffic shares the available bandwidth with CCH traffic. At the physical (PHY) layer level, sharing is accomplished through separation of resources, i.e., preambles used for random access. At the medium access (MAC) layer level, the four step handshake is eliminated through the use of a carrier sense multiple access with collision avoidance (CSMA-CA) overlay [15] similar to IEEE 802.15.4 standard [17], [18]. The main challenge, in this case, is to devise the scheme in which both SCH and CCH traffic can enjoy fair access the available LTE bandwidth. This approach, hereafter denoted as vehicular M2M (VM2M) overlay, is described and evaluated in the current paper. We investigate the capacity of both sub-networks in a number of scenarios, and we show that the VM2M overlay allows fair coexistence of VM2M and H2H traffic.

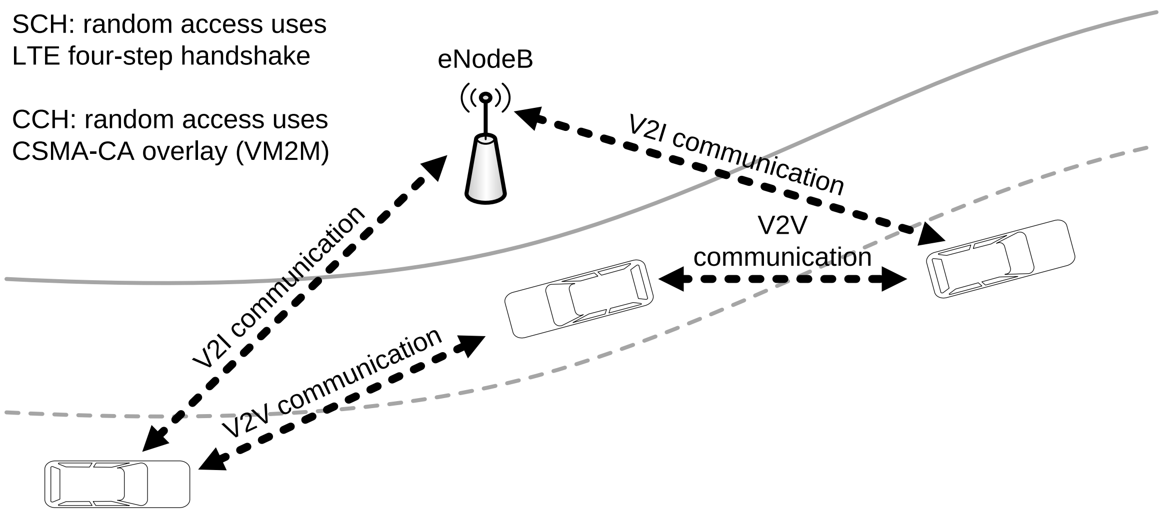
The rest of the paper is organized as follows: VANET architecture with LTE and its challenges are discussed in Section 2, while the proposed VM2M overlay is presented in Section 3. In Section 4 we present the overlay network, followed by performance evaluation of H2H and VM2M traffic. Finally, Section 5 concludes the paper.

2 LTE-Based VANET: SCH

Conceptual architecture of a VANET implemented via LTE is shown in **Fig. 1**. We distinguish between SCH which uses regular LTE access and CCH which uses the VM2M overlay, as we explain in the following.

SCH traffic uses regular LTE access where a mobile terminal (MT—in this case, an OBU) that has no allocated radio resources must first perform random access to connect to the network. Random access can be contention-based, in case of a new connection, or contention-free; in the former case, the standard-prescribed four step handshake is used.

1) MT randomly selects one of the set of N_{ZC} preambles, as will be explained below, and transmits it over PRACH to eNodeB.
2) eNodeB transmits a random access response (RAR) message back to MT through the downlink shared channel (PDSCH). RAR contains the decoded preamble, as well as temporary Cell Radio Network Temporary Identifier (CRNTI) and scheduling information for the third step.



CCH: control channel
CSMA-CA: carrier sense multiple access with collision avoidance
SCH: service channel
V2I: vehicle to infrastructure
V2V: vehicle to vehicle
VM2M: vehicular machine-to-machine
Figure 1. Vehicular communication through LTE.

3) MT sends its CRNTI and scheduling information to eNodeB through physical uplink shared channel (PUSCH) radio resources assigned in the step 2.

4) Finally, eNodeB responds with the confirmation of the identity of MT and finishes the contention procedure.

Contention-free access is used in case of a handover from a cell controlled by another eNodeB; it follows a slightly simpler three-step handshake [13].

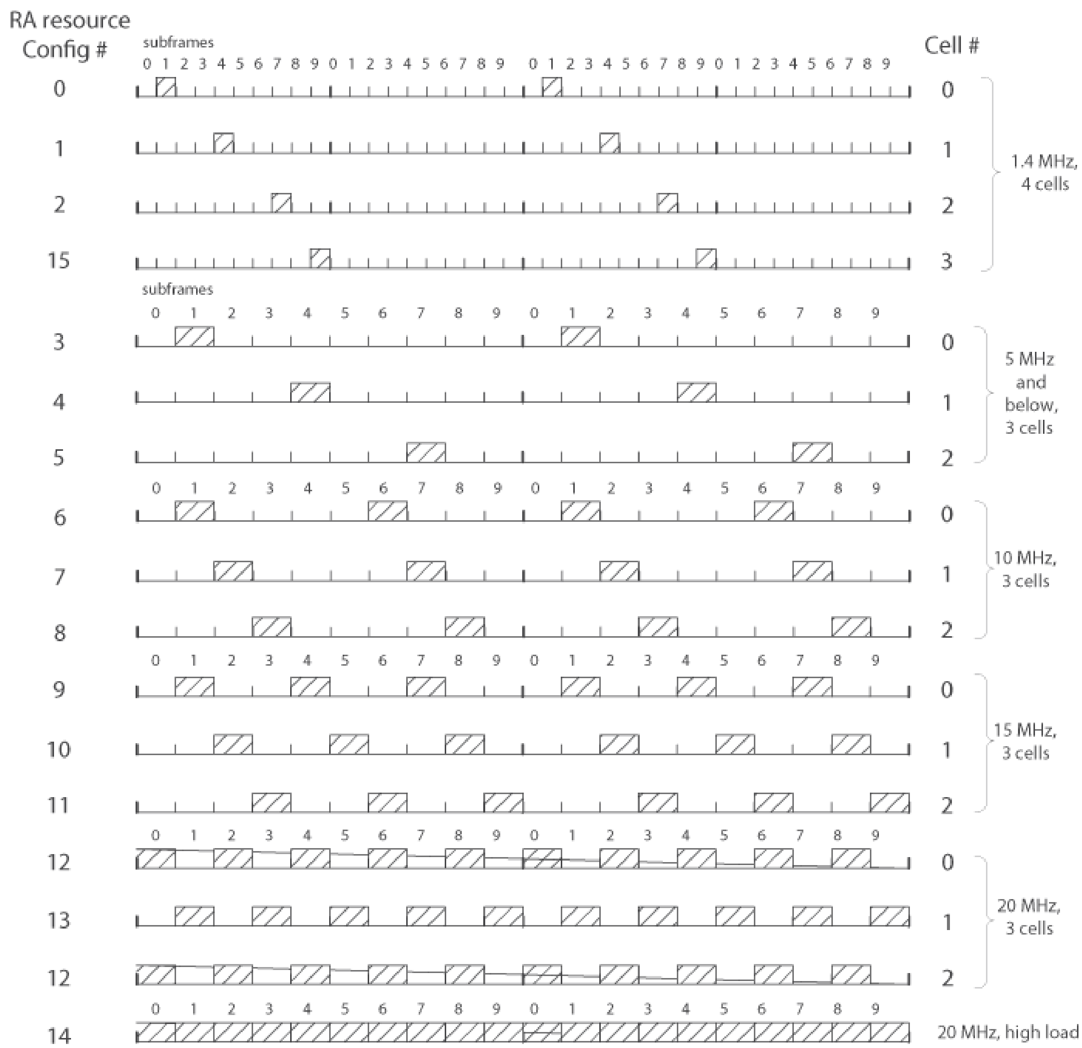
Unfortunately, first and third steps of the four step handshake are prone to collisions and overload conditions which prevent completion of handshake [15]. Collisions occur when two or more MTs choose the same preamble in the first step of the handshake. Preambles are a set of mutually orthogonal Zadoff-Chu (ZC) sequences derived from a single base sequence by adding cyclic shifts. One base sequence gives $N_{ZC} = 64$ sequences; larger number of preamble sequences can be obtained by using two or more base sequences. A certain number of preambles are reserved for contention-free access, while the remaining ones are allocated for contention mode.

PRACH is configured as a dedicated resource in a LTE frame, possibly shared with other physical channels such as PDSCH and PUSCH [14]. Namely, the bandwidth available in LTE is structured in a time- and frequency-domain matrix. Time-wise, access is organized in frames that last 10 ms and consist of 10 subframes with duration of 1 ms each, which can be further divided into two 0.5 ms slots. In the frequency domain, resources are grouped in units of 12 OFDM subcarriers with a total bandwidth of 180 kHz. Basic access unit for either random or scheduled access is a resource block (RB) consisting of 12 sub carriers over one subframe duration of 1 ms. For control channels, an even finer granularity is available where the smallest resource unit is a resource element (RE) consisting of one sub-carrier for the duration of one OFDM symbol.

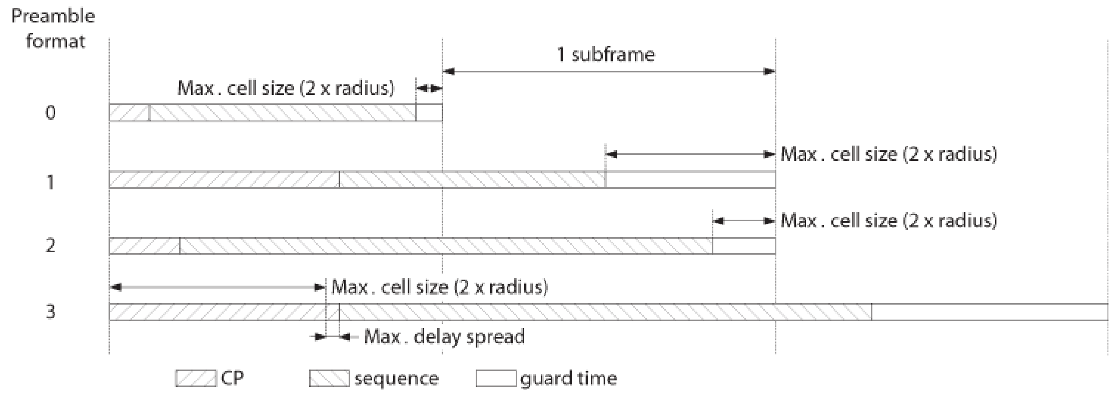
Cell bandwidth can be configured for frequency- or time-division duplex access (FDD or TDD, respectively). In the TDD configuration, there is a single carrier frequency which is alternatively used for uplink and downlink transmissions. In this case, subframes 0 and 5 are always reserved for downlink transmission while subframe 2 is always used for uplink; other subframes can be used for uplink or downlink transmissions as necessary. To minimize congestion due to interference, neighboring cells typically use the same uplink/downlink configuration.

Minimum PRACH configuration uses six resource blocks in a single subframe in two consecutive frames, resulting in a 1.080 MHz bandwidth (TDMA configurations 0, 1, 2 and 15); it suffices at low traffic intensity and small system bandwidth. At higher traffic volume, PRACH resource may be configured to occur once per frame (TDMA configurations 3, 4, and 5); once per five subframes, i.e., twice in each frame (TDMA configurations 6, 7 and 8); or even once per three subframes (TDMA configurations 9, 10 and 11). Although previous PRACH allocations avoided interference at granularity of 3 cells, dense PRACH allocations bring the possibility of interference at high traffic volume since PRACH resource occurs on every second subframe (configurations 12 and 13) or on every subframe in a frame (configuration 14). The configurations are schematically shown in **Fig. 2a**.

To accommodate different attenuations and propagation delays for various cell sizes, four preamble formats, denoted as 0, 1, 2, and 3, are defined. High attenuation is addressed by increased preamble duration, while the cyclic prefix (CP) and guard time (GT) are used to avoid delays and minimize interference with the adjacent subframes. Format 0 preamble duration is 800 μs, with a combined total of CP and GT lasting for an additional 200 μs; formats 2 and 3 use longer preamble duration of 1600 μs. Furthermore, formats 1 and 2 fit in two consecutive subframes while format 3 fits in three consecutive subframes. In the default case of preamble format 0 with W = 1.08 MHz PRACH bandwidth and 5MHz system bandwidth, the preamble length is 839 elements and the resulting preamble element rate is R=1.048 M elements per second. However, in vehicular scenario with high vehicle speeds over longer distances, more PRACH resources are needed in each 10 ms LTE frame: for example, format 2 with double preamble duration over two consecutive subframes. In this case, the signal to interference and noise ratio (SINR) threshold is $10\,log\,(E_p/N) = 15$ dB, which improves the power budget by 3 dB over the default format 0 where the SINR threshold is 18 dB. The formats are schematically shown in **Fig. 2b**.



(a) PRACH resource configurations



(b) PRACH preamble formats

CP: cyclic prefix
RA: random access
Figure 2. Pertaining to PRACH configurations and formats, after [14].

3 LTE-Based VANET: VM2M Overlay for CCH

In our approach, CCH is allowed to share the PRACH with regular (SCH) traffic. However, random access on PRACH can fail due to the following two mechanisms.

First, as the number of preambles is limited (the default number is 64 per cell), a collision may occur when two or more MTs select the same preamble for initial access [19], [20]. Collided preambles are re-transmitted after a random backoff that spreads out access to maximize the probability of success [21].

Second, congestion can occur on account of noise and interference generated by other nodes, both in the same cell and in neighboring cells, as other logical channels may use some of the resources of the PRACH in the current cell. It may occur in both the first and third steps of the handshake. However, in absence of congestion, eNodeB might be able to decode a preamble even upon a collision and subsequently grant access to one of the terminals; this is known as capture effect.

Congestion was shown to be a much bigger problem than collisions [15], partly due to the fact that the four step handshake is effectively an overkill for CCH messages which are short and occur in random bursts [10]. We note that one of the key challenges identified by 3GPP is how to control the overload and congestion in case of simultaneous access by tens of thousands of M2M devices [22]. Random access could be made more efficient if safety messages on the CCH could be decoded without requiring the terminal to go through the complete handshake.

Following the approach described in detail in [15], we propose to implement CCH in the following manner. At the PHY level, a total of N_c preambles is reserved for CCH; this number need not be high—typically, 8 or 10 preambles out of 64 would suffice—as the aggregate traffic volume on CCH is much lower than that on SSH. Reserving the preambles for CCH use will accomplish resource separation at the preamble level and reduce the potential for collisions with SSH messages. The remaining preambles will be used for new and handover connections, and potentially for other overlay networks as well. Once the connection is established, SCH traffic such as infotainment and vehicular telematics can use any other scheduled channel available in

LTE.

Data bits of a CCH message will be multiplexed over the reserved preambles. In addition, preamble elements used as a chipping sequence for a single data bit; this will improve the SINR for the overlay because of the detection mechanism. Namely, SINR for detecting a regular (i.e., H2H or SCH) preamble is based on the entire preamble duration. On the other hand, the SINR threshold for detecting a preamble in the overlay must hold for each bit in the preamble. As the result, the latter SINR is higher than the former.

At the MAC level, the preambles reserved for CCH are used to implement a slotted CSMA-CA MAC protocol similar to IEEE 802.15.4 [17], [18]. Assuming that one backoff slot has 20 sequence elements, we obtain the unit backoff time as $t_{boff} = 20/R = 18.51\,\mu$s, which is close to the value of $20\,\mu$s used in IEEE 802.11 at the raw data rate of 1 Mbps.

Time for preamble transmission (typically, 0.8 ms) becomes the superframe time for VM2M overlay network. The whole LTE frame duration is 540 overlay backoff periods. The time interval between two active periods/ superframe is the distance between two beacons, i.e., the period between two PRACH subframes. It depends on the PRACH configuration parameter c_f, i.e., on the number of PRACH resources available in the LTE frame time and calculated as $PB = 540/c_f$. The active portion of the superframe, then, has the size of $N_{ZC}N_c/8N_b$; the guard time and cyclic prefix may be understood as the superframe inactive time [17]. Note that this is conceptually different from the BO and SO parameters that regulate active superframe size and distance between consecutive beacons in the original IEEE 802.15.4 standard [18].

The superframe will begin immediately after the reception of beacon and after completing the random backoff, and the terminal will transmit the message to eNodeB. EnodeB will acknowledge a successfully decoded message. Non-acknowledged messages will be retransmitted until successful or until the retransmission limit is reached. When the CCH queue is found to contain a packet to transmit, the terminal (i.e., the OBU) synchronizes with the beacon and begins the CSMA-CA transmission algorithm. It picks a random backoff value, counts down to zero (decrementing the backoff value at the boundary of the current backoff period), and checks whether the medium is busy in two successive backoff slots. If it finds that the medium is busy, the terminal initiates a new backoff countdown. If not, it transmits the packet using the preamble sequence in the manner described above. Also, if the current superframe does not have enough time to finish the countdown, the node needs to wait until the next superframe active period.

In this manner, CCH traffic—typically, safety messages—can be sent quickly without going through the four step handshake, while SCH traffic can go the regular route, first by creating a connection through PRACH and then using other LTE scheduled channels for actual content.

4 Performance of the VM2M Overlay Network

To evaluate the performance of the proposed VM2M overlay scheme, we have used the analytical model described in detail in [15]; the resulting set of equations was solved using Maple 16 from Maplesoft, Inc. [23]. Our primary objective was to determine feasible combinations of configuration formats and parameter values that would allow for simultaneous CCH and SCH access on PRACH. We assume that the number of preamble codes per cell is $N = 64$; the number of preambles reserved for handoff is $N_h = 10$ while the number of preambles reserved for physical layer of the VM2M overlay is $N_c = 8$. This leaves $N_i = 46$

preambles for H2H access. One data bit in overlay VM2M network is spread over $N_b = 16$ preamble elements. The required detection threshold for format 0 is $10log\,(E_p/N_0) = 18$ dB and for format 2 threshold is 15 dB. The corresponding mean ratio of bit energy and noise spectral power density is $10log\,(E_b/N_0) = -11.23$ dB, for format 0, and -14.25 dB for format 2; the corresponding overload thresholds are $T_1 = 0.0752$ and 0.038, respectively.

For the third handshake step in which L2/L3 messages are transmitted by fewer terminals, we assume bandwidth to data rate ratio of $W_3/R_3 = 1$, and the mean ratio of bit energy and noise spectral power density is $10log\,(E_b/N) = -5$ dB [14]. We consider maximum number of colliding terminals to be 5 which seemed reasonable, in particular for vehicular applications.

For both SCH and CCH overload cases, we modeled inter-cell interference as a Gaussian random variable with mean $k_{m,1} = k_{m,3} = 0.247$ and standard deviation $k_{v,1} = k_{v,3} = 0.078$. White noise density was set at $n_0 = 4.10^{-21}$ W/Hz.

4.1 Performance for SCH Traffic

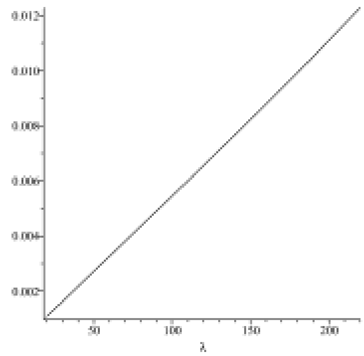
In this section we present the results of a set of experiments focusing on PRACH capacity for SCH traffic when $N_M = 8$ preambles are permanently set aside for the VM2M overlay, under variable intensity of SCH traffic.

In the first experiment, we compare scenarios of configuration 2, format 0 (c_f=2, PF=0) with that of configuration 1, format 2 (c_f=1, PF=2) when the new call arrival rate on SCH is varying between 20 and 220 requests per second. Although PRACH bandwidth allocations look similar, performance metrics show some subtle differences. From **Figs. 3a** and **3d**, the use of configuration 2, format 0 means that 2 independent PRACH resources are available in one LTE frame, each of which has a preamble duration of 800 μs. On the other hand, preamble format 2 with configuration 1 means that a single PRACH resource is used two consecutive subframes, but that the same preamble is transmitted twice, with a total duration of 1600 μs. Therefore second combination will gain in power budget but lead to one wasted time opportunity per LTE frame. The improvement in power budget is $10\log_{10}(2E_s/N_0) = 10\log_{10}(2) + 10\log_{10}(E_p/N_0) = 3dB + 10\log_{10}(E_p/N_0)$, where E_s/N_0 is energy per symbol to noise power spectral density and E_p/N_0 represents the ratio of preamble sequence energy to noise power density per Hz. As the result, the preamble detection threshold for format 2 is 3 dB, lower than the threshold for format 0, i.e. they are equal to 15 dB and 18 dB respectively.

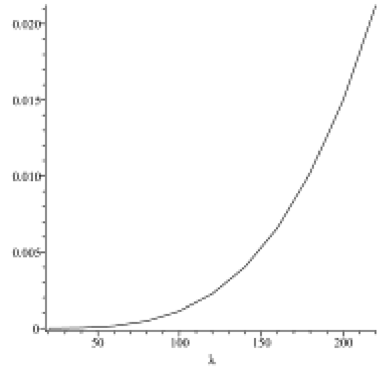
The preamble collision probability when format 2 is used (**Fig. 3d**) is higher than when format 0 is used (**Fig. 3a**). This is due to the fact that the preambles that have collided in the first slot of the frame are subsequently repeated in the second subframe for format 2.

Regarding overload probability, **Figs. 3b** and **3e** confirm that using format 2 leads to much reduced likelihood of SINR violation compared to format 0, where the overload probability is nearly 2% under the maximum load.

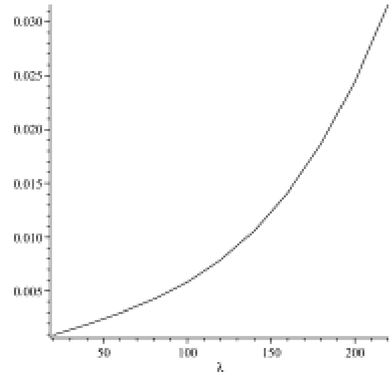
Since overload has much more impact on preamble success than preamble collisions [15], total probability of access failure is much lower when format 2 is used (**Fig. 3f**) than the corresponding value when format 0 is used (**Fig. 3c**). In fact, if we impose the limit of 2% onto acceptable failure probability, as is customary in LTE [13], [14], we may conclude that format 0 results in usable call arrival rate (in other words, cell capacity) of about 180 new calls per second, while format 2 can achieve the capacity of about 210 new calls per second.



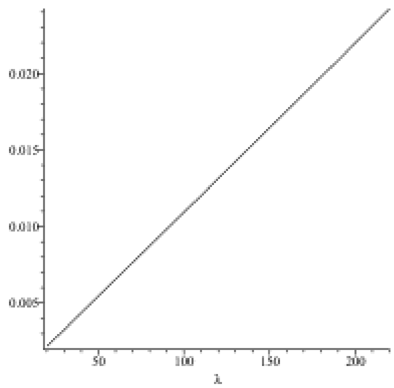
(a) Probability of code collision, $PF = 0$, $c_f = 2$.



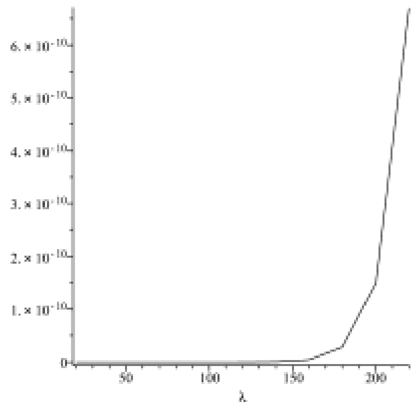
(b) Probability of overload, $PF = 0$, $c_f = 2$.



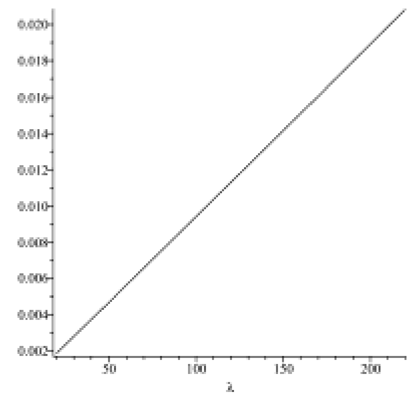
(c) Probability of access failure, $PF = 0$, $c_f = 2$.



(d) Probability of code collision, $PF = 2$, $c_f = 1$.



(e) Probability of overload, $PF = 2$, $c_f = 1$.



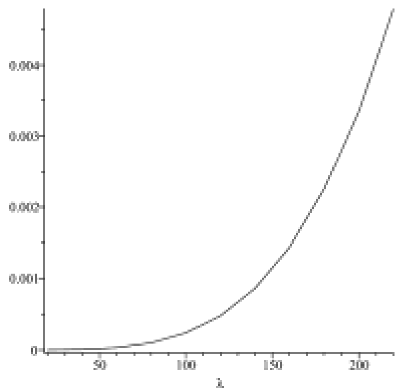
(f) Probability of access failure, $PF = 2$, $c_f = 1$.

Figure 3. Performance of the four step handshake for SCH traffic, at small PRACH configurations. In all diagrams, horizontal axes show the new call arrival rate in calls per second, while the vertical axes depict the respective probabilities.

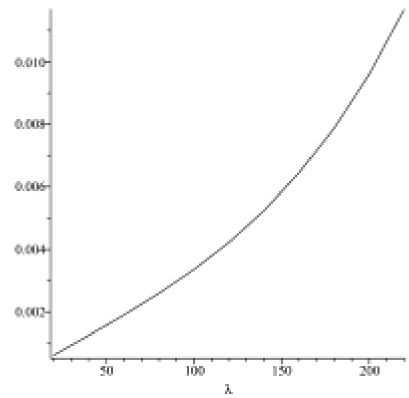
In our second experiment, we compare the performance for SCH calls of scenario under preamble format 0, configurations 3 and 5, and format 2, configuration 2. These scenarios provide similar, though not quite identical, subframe allocation for PRACH and, consequently, allow nearly fair performance comparison. Note that preamble format 0 with configuration 3 has three PRACH resources with 0.8 ms preamble duration in a single LTE frame, while preamble format 0 with configuration 5 has as many as 5 PRACH resources in that same time interval; the combination of preamble format 2 with configuration 2 means that preamble duration is 1.6 ms while a single LTE frame has a total of $2 \cdot 2 = 4$ subframes that are allocated for random access. The resulting performance is shown in the diagrams in **Fig. 4**.

We observe that, when format 0 is used, increasing the number of PRACH resources in a single LTE frame leads to improved performance: reduction of overload probability for configuration 5 (**Fig. 4d**) to about one-seventh of the value obtained for configuration 3 (**Fig. 4a**). Moreover, probability of access failure is also smaller for configuration 5 (**Fig. 4e**) than for configuration 3 (**Fig. 4b**).

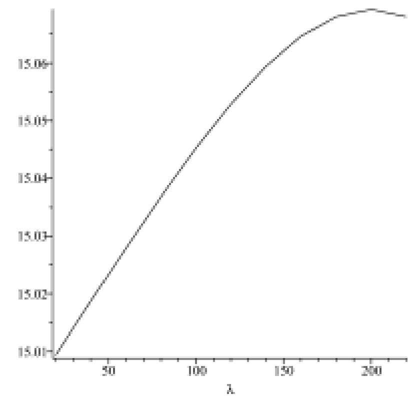
An even greater reduction of overload probability can be obtained with preamble format 2 with double preamble transmission time (**Fig. 4g**), mainly on account of larger power budget for preamble detection. However, the probability of access failure in this scenario (**Fig. 4h**), is comparable to that obtained in the previous two scenarios: about the same as for format 0, configuration 3 (**Fig. 4b**) and slightly higher than for format 0, configuration 5 (**Fig. 4e**). Extrapolating the curves shown in **Figs. 4h**, **4b**, and **4e**, we may conclude that the SCH subnetwork capacity at up to 2% handshake failure rate, is around 400 new calls per second for format 2, configuration 2, around 300 and 500 for format 0, configuration 3 and 5, respectively.



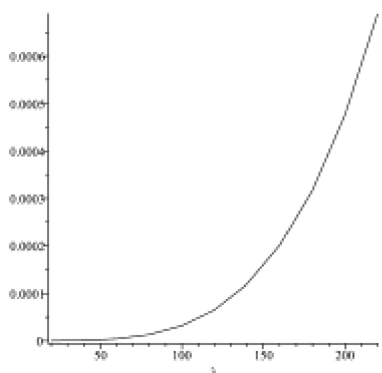
(a) Probability of overload, $PF = 0$ and $c_f = 3$.



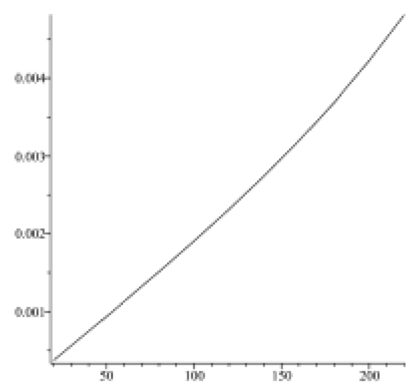
(b) Probability of access failure, $PF = 0$ and $c_f = 3$.



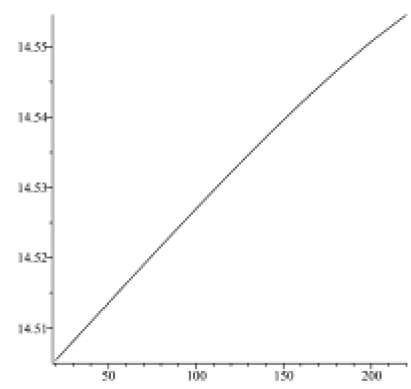
(c) Mean access delay, $PF = 0$ and $c_f = 3$.



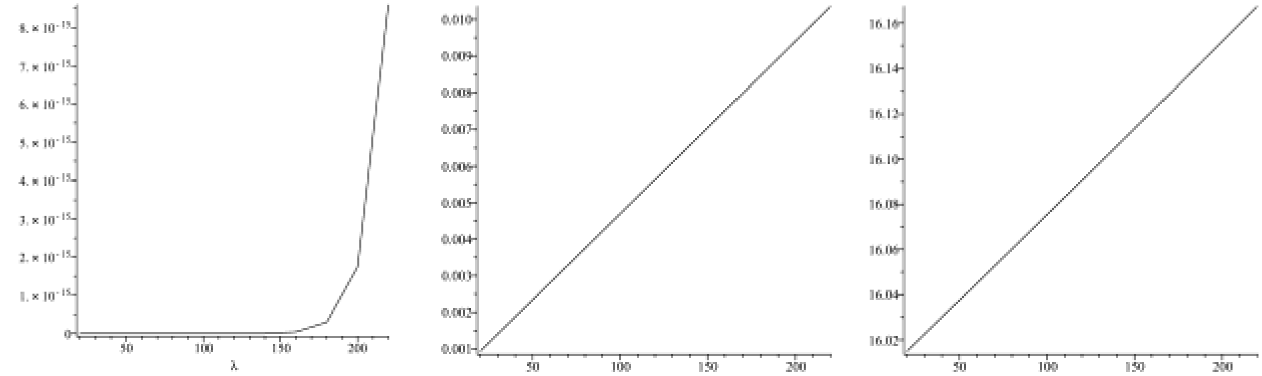
(d) Probability of overload, $PF = 0$ and $c_f = 5$.



(e) Probability of access failure, $PF = 0$ and $c_f = 5$.



(f) Mean access delay, $PF = 0$ and $c_f = 5$.



(g) Probability of overload, $PF = 2$ and $c_f = 2$

(h) Probability of access failure, $PF = 2$ and $c_f = 2$.

(i) Mean access delay, $PF = 2$ and $c_f = 2$.

Figure 4. Performance of the four step handshake for SCH traffic, at large PRACH configurations. In all diagrams, horizontal axes show the new call arrival rate in calls per second. Vertical axes in the diagrams in the leftmost and center column depict the respective probabilities, while the vertical axes in the diagrams in the rightmost column show mean access delay in *ms*.

We have also calculated the access delay, shown in the rightmost column of **Fig. 4**; the diagrams show that the delays are nearly unaffected by these variations in PRACH format and configuration: the difference between delays in different scenarios is at most 10%.

The conclusion to be made from these experiments is that, for small PRACH allocations, the use of format 2 and configuration 1 has higher capacity compared to the scenario in which format 0 and configuration 2 are used. For large PRACH allocations, the scenario that uses preamble format 0 and PRACH configuration 5 offers highest capacity and shortest access delay. However, better performance does come at a cost: providing more PRACH resources per LTE frame leads to a reduction in usable bandwidth for other scheduled channels.

4.2 Performance Evaluation of VM2M Overlay Network

In the second set of experiments, we have investigated the performance of VM2M overlay for CCH traffic, under different values of SCH new call arrival rate. As before, we assumed that $N_c = 8$ preamble codes are dedicated for implementing the physical layer of the VM2M overlay. Preamble formats are set to 0 and 2, respectively. The superframe consists of active and inactive periods according to distances between PRACH resources. As one backoff period has 20 sequence elements and one bit requires $N_b = 16$ preamble elements, one backoff period can accommodate $20N_c/(8N_b)$ bits. The superframe duration for format 0 and 2 is $N_{ZC}/20 = 41$ and 82 backoff periods, respectively. Duration of the entire PRACH resource is 54 and 108 backoff periods respectively. The beacon interval between two PRACH resources is $540/c_f$ for both formats. In this work we assume that data packet size is 30 bytes including 10 bytes for MAC headers and 20 bytes for actual data, which should contain cell and node IDs.

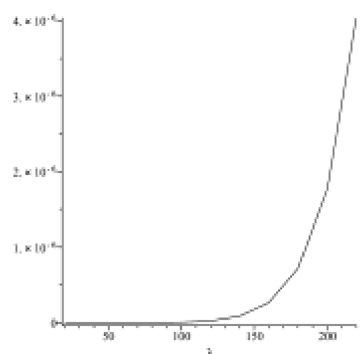
MAC parameters for VM2M overlay are set as follows. The backoff exponent BE is initially set to minimum value of $macMinBE = 3$ giving the initial backoff window in the range $0..7$. After an access failure, backoff exponent is incremented by one until it reaches the maximum value of $aMaxBE = 5$. The contention window value is set to $w = 2^{BE}$ and the maximum number of backoff attempts is set to $MaxCSMABackoffs = 5$. Buffer size in VM2M device was set to 3 packets which is sufficient for real time safety messages.

We have calculated success probability as the product of probabilities that packet is not corrupted and that packet has not collided with other packet. To investigate the capacity limit of the VM2M overlay, we varied the number of VM2M devices between 200 and 950; packet arrival rate per device was varied from 0.2 to 1 arrival per minute. We also evaluated fairness in capacity allocation to VM2M subnetwork under constant arrival rate of SCH traffic, similar to the experiments described above.

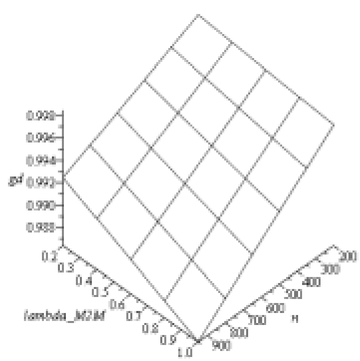
We first compared the scenarios with format 0 and configuration 2 with those with format 2 and configuration 1. The SCH new call arrival rate was set to 100 and 220 calls per second, respectively. The results are shown in **Fig. 5**.

The first observation is that overload probability is much lower for PRACH format 0 than for format 2 with same time occupancy in LTE frame, as shown in **Figs. 5a** and **5d**, respectively. This is contrary to our findings for the overload probability in case of SCH traffic which is much higher for PRACH format 0 compared to format 2. The discrepancy may be explained by noting that the preamble repetition in format 2 creates much stronger interference to VM2M overlay than a single preamble transmission with one-half traffic intensity, as is the case in format 0, configuration 2.

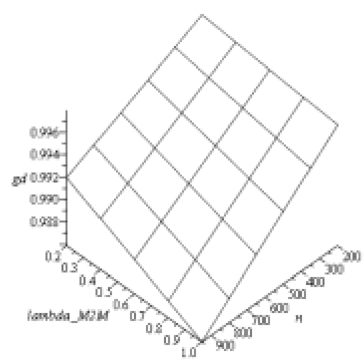
Regarding the probability of successful access, format 0 with configuration 2 (**Fig. 5**) shows that the VM2M overlay can easily achieve success ratio over 98.8%, even at the SCH new call arrival rate of 220 per second, within the observed range of VM2M network sizes and traffic intensity. Assuming the packet failure rate threshold of 2%, the VM2M overlay can easily support as many as 1200 devices. The failure rate is much higher, up to about 10%, in case format 2, configuration 1 is used (**Fig. 5**).



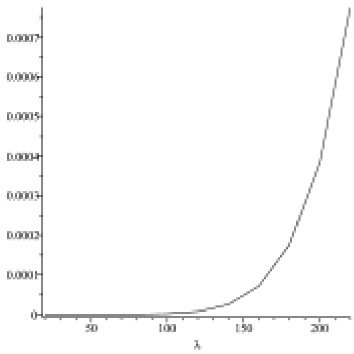
(a) Probability of overload, $PF = 0$ and $c_f = 2$.



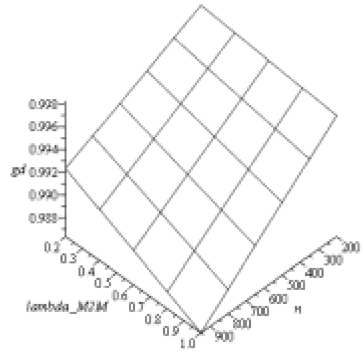
(b) Probability of successful access, SCH arrival rate is 100 calls per second, $PF = 0$ and $c_f = 2$.



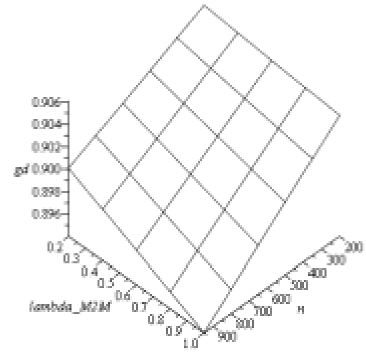
(c) Probability of successful access, SCH arrival rate is 220 calls per second, $PF = 0$ and $c_f = 2$.



(d) Probability of overload, $PF = 2$ and $c_f = 1$.



(e) Probability of successful access, SCH arrival rate is 100 calls per second, $PF = 2$ and $c_f = 1$.

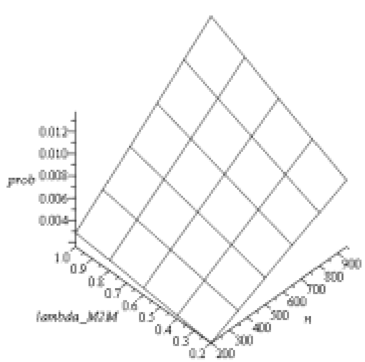


(f) Probability of successful access, SCH arrival rate is 220 calls per second, $PF = 2$ and $c_f = 1$

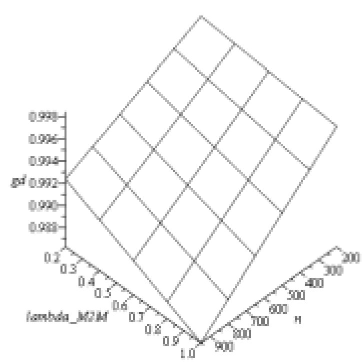
Figure 5. Performance parameters for CCH traffic through the VM2M overlay at small PRACH allocations. In all diagrams, horizontal axes show the new call arrival rate in calls per second, while the vertical axes depict the respective probabilities.

In the second experiment we consider large PRACH allocations: format 0 with configurations 3 and 5, and format 2 with configuration 2, similar to the second experiment in the previous subsection. The results are shown in **Fig. 6**. In all cases, VM2M call arrival rate was varied between 0.2 and 1 call per minute.

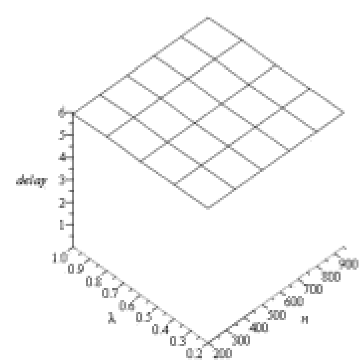
As can be seen, large superframe size obtained in configuration 5 leads to reduced overload probability compared to the case with configuration 3. However, overload probability for format 2 is higher due to repeating of preamble transmission in PRACH resource. Probability of successful access is close to one in all cases.



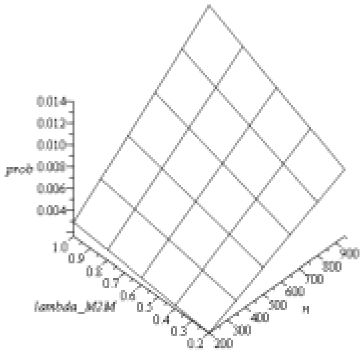
(a) Collision probability, PF=0, c_f=3.



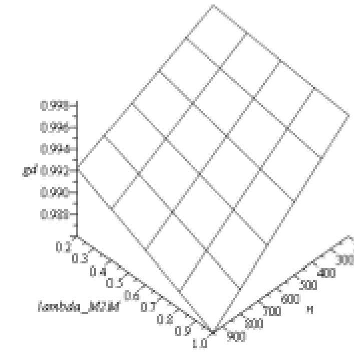
(b) Probability of successful access, PF = 0, c_f=3.



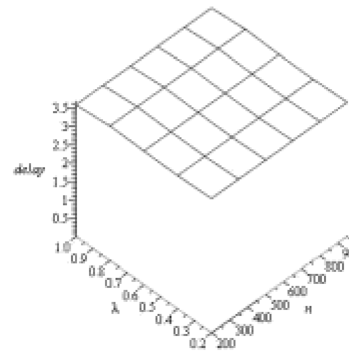
(c) Access delay, PF =0, c_f=3.



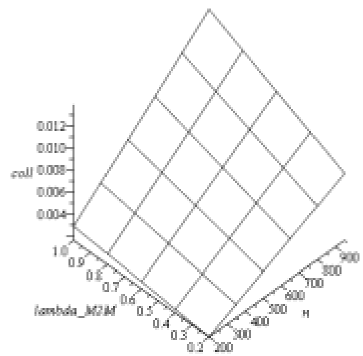
(d) Collision probability, PF = 0, c_f=5.



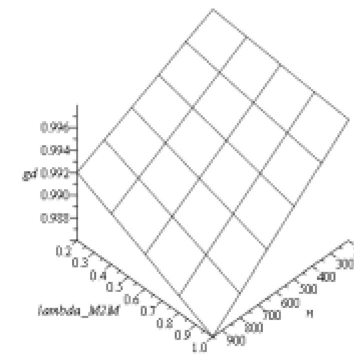
(e) Probability of successful access, PF = 0, c_f=5.



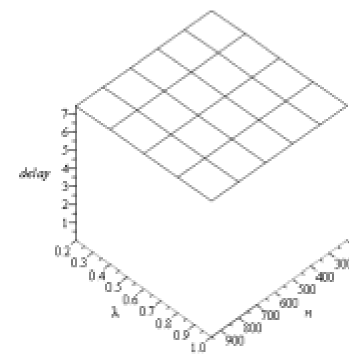
(f) Access delay, PF = 0, c_f=5.



(g) Collision probability, PF = 2, c_f=2.



(h) Probability of successful access, PF = 2, c_f=2.



(i) Access delay, $PF = 2$, $c_f = 2$.

Figure 6. Performance parameters for CCH traffic through the VM2M overlay at large values of configuration parameters; SCH arrival rate 220 calls per second. In all diagrams, horizontal axes show the new call arrival rate in calls per second. Vertical axes in the diagrams in the leftmost and center column depict the respective probabilities, while the vertical axes in the diagrams in the rightmost column show mean access delay in *ms*.

Access delay for format 0 decreases with the increase in the number of PRACH resources (configurations 3 and 5, respectively). Delay for format 2, configuration 2, is larger compared to format 0 due to larger distance between the superframes. However, all VM2M access delays are lower than their SCH counterparts.

4.3 Discussion

Our results have shown that for small PRACH allocations, the SCH subnetwork has about 20% larger capacity for format 0 and configuration 2, compared to format 2, configuration 1. The VM2M overlay under format 0, configuration 2, can accommodate around 1000 terminals at traffic intensity of one packet per minute, whilst the SCH subnetwork can simultaneously service 220 new requests per second at the probability of successful access of 0.98 or higher.

Unfortunately for format 2, configuration 1, comparable CCH capacity can be achieved only under 100 SCH requests per second. This puts proper functioning of the VM2M overlay (and, consequently, capacity for safety messages) in jeopardy if the SCH request rate is not limited.

For larger PRACH allocations, format 2 with configuration 2 offers just about 20% higher capacity at about 5% longer delay in comparison with format 0 and configuration 3; unfortunately, this hardly justifies the 30% increase in subframe allocation for the PRACH. Configuration 5 with format 0 has almost 25% increase in subframe allocation and similar increase in capacity, but with shorter access time.

With respect to the capacity of the VM2M overlay, all three combinations can accommodate up to 1000 OBUs at the transmission rate of 1 packet per OBU per minute. In all cases, access delays for VM2M (CCH) overlay are significantly lower compared to the SCH subnetwork, which is the result of eliminating the four step handshake for CCH traffic.

Regardless of the PRACH format, increasing the frame configuration parameter will almost linearly increase the capacity for both SCH and VM2M subnetworks and, at the same time, decrease the access time. However, at high portion of PRACH allocations, care has to be taken to avoid interference with PUSCH transmission in surrounding cells which can increase PRACH interference and decrease the capacity of the VM2M overlay.

Unfortunately, the choice of preamble format is not entirely up to us but, rather, depends on the environment. For sub-urban, rural and highway scenarios, PRACH format 2 or even 3 might be necessary due to large vehicle speed and long round-trip times. Use of format 2 increases the power budget and gives the priority to SCH traffic since each preamble is transmitted twice. In this scenario, the VM2M overlay network is penalized as it suffers from higher interference. For urban environments, PRACH format 0 can be used, in which case the capacity can be increased by increasing the PRACH configuration parameter.

We note that the overlay network mainly impacts SCH traffic in a deterministic manner: i.e., by reducing the number of available preambles by N_c. On the other hand, variable rates of SCH requests present random interference to CCH traffic that uses the VM2M overlay which is a much bigger challenge. Capacity of M2M overlay can be increased by increasing the number of preambles N_c used in the VM2M physical layer. This is also beneficial from the aspect of CSMA/CA since superframe capacity will increase and packet access can be spread more evenly over the superframe duration.

5 Conclusions and Future Work

In this paper we proposed an approach to implement vehicular access over LTE. CCH is implemented as an PRACH overlay network and SCH can be implemented as regular LTE traffic. We have analyzed impact of PRACH format and configuration parameter on the performance of SCH and VM2M subnetworks, and outlined some performance limitations coming from double preamble transmission in format 2 which is necessary for large cells covering sub-urban, rural areas and highways. In our future work, we will propose a dynamic scheme to change the PRACH format and configuration according to the traffic volume and other environmental factors. We will also investigate the possibility of dynamically changing the number of preambles used for the physical layer of the VM2M overlay.

References

[1] IEEE Standard for Information Technology-Telecommunications and Information Exchange Between Systems-Local and Metropolitan Area Networks-Specific Requirements - Part II: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 6: Wireless Access in Vehicular Environment. IEEE, New York, NY, 2010.

[2] C. Campolo and A. Molinaro. Data rate selection in WBSS-based IEEE 802.11p/WAVE vehicular ad hoc networks. *Proc. CSNDSP*, pp. 412–416, July 2010.

[3] J. Mišić, G. Badawy, and V. B. Mišić. Performance Characterization of IEEE 802.11p Networks With Single Channel Devices. *IEEE Trans. Vehicular Technology*, vol. 60, no. 4, pp. 1775–1787, May 2011, DOI: 10.1109/TVT.2011.2116052.

[4] S. Öztürk, J. Mišić, and V. B. Mišić. Reaching spatial or networking saturation in VANET. *EURASIP J. Wireless Comm.*, pp. 1–12, November 2011, DOI: 10.1186/1687-1499-2011-174.

[5] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro. LTE for vehicular networking: a survey. *IEEE Communications Magazine*, vol. 51, no. 5, pp. 148–157, May 2013, DOI: 10.1109/MCOM.2013.6515060.

[6] Hameed Mir, Z., Filali, F., "LTE and IEEE 802.11p for vehicular networking: a performance evaluation," *EURASIP J. Wireless Comm. Networking*, vol. 2014, no. 1, article 89, 2014, DOI: 10.1186/1687-1499-2014-89.

[7] S. Uçar, S. Çöleri Ergen, and Ö. Özkasap. Multi-Hop Cluster based IEEE 802.11p and LTE Hybrid Architecture for VANET Safety Message Dissemination. *IEEE Trans. Vehicular Technology*, vol. 65, no. 4, pp. 2621–2636, April 2015, DOI: 10.1109/TVT.2015.2421277.

[8] A. Vinel. 3GPP LTE Versus IEEE 802.11p/WAVE: Which Technology is Able to Support Cooperative Vehicular Safety Applications? *IEEE Wireless Communications Letters*, vol. 1, no. 2, pp. 125–128, April 2012, DOI: 10.1109/WCL.2012.022012.120073.

[9] E. Hossain, G. Chow, V. C. Leung, R. D. McLeod, J. Mišić, V. W. S. Wong, and O. Yang. Vehicular telematics over heterogeneous wireless networks: A survey. *Computer Communications*, vol. 33, no. 7, pp. 775–793, 2010, DOI:10.1016/j.comcom.2009.12.010.

[10] G. Badawy, J. Mišić, T. Todd, and D. Zhao. Performance modeling of safety message delivery in vehicular ad hoc networks. *IEEE Int. conf. Wireless and Mobile Computing, Networking and Communications (WiMob'2010)*, pp. 188–195, October 2010, DOI: 10.1109/WIMOB.2010.5644987.

[11] H. Abid, T.-C. Chung, S. Lee, and S. Qaisar. Performance analysis of LTE smartphones-based vehicle-to-infrastructure communication. *Proc. UIC/ATC*, pp. 72–78, 2012, DOI: 10.1109/UIC-ATC.2012.155.

[12] V. DhilipKumar, D. Kandar, and C. K. Sarkar. Enhancement of inter-vehicular communication to optimize the performance of 3G/4G-VANET. *Proc. Int. Conf. Optical Imaging Sensor and Security (ICOSS)*, pp. 1–5, July 2013.

[13] E. Dahlman, S. Parkval, and J. Skold. *4G: LTE/LTE-Advanced for Mobile Broadband*. Academic Press, 2009.

[14] S. Sesia, I. Toufik, and M. Baker. *LTE, The UMTS Long Term Evolution: From Theory to Practice*. John Wiley and Sons, 2009.

[15] J. Mišić, V. B. Mišić, and N. Khan. Sharing It My Way: Efficient M2M Access in LTE/LTE-A Networks. to appear in *IEEE Transactions on Vehicular Technology*, 2016, DOI: 10.1109/TVT.2016.2547910.
[16] V. B. Mišić and J. Mišić. *Machine-To-Machine Communications – Architectures, Technology, Standards, and Applications.* Boca Raton, FL: CRC Press, 2014.
[17] 802.15.4-2011 - IEEE Standard for Local and metropolitan area networks–Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs).
[18] J. Mišić and V. B. Mišić. *Wireless Personal Area Networks: Performance, Interconnection and Security with IEEE.802.15.4.* John Wiley & Sons, 2008.
[19] 3GPP TSG RAN WG2 71bis R2-104663, LTE: MTC LTE simulations. Technical report, August 2010.
[20] Z. Kaijie and N. Nikaein. "Packet aggregation for machine type communications in LTE with random access channel," *Wireless Communications and Networking Conference (WCNC'2013)*, pp. 262–267, April 2013, DOI: 10.1109/WCNC.2013.6554574.
[21] Y. Chen and W. Wang. Machine-to-Machine Communication in LTE-A. *IEEE Vehicular Technology Conference (VTC 2010-Fall)*, pp. 1–4, Septtember 2010, DOI: 10.1109/VETECF.2010.5594218.
[22] 3GPP. TS 37.868 V11.0. Study on RAN Improvements for Machine Type Communications. Technical report, October 2011.
[23] Maplesoft, Inc. *Maple 16*. Waterloo, ON, Canada, 2013.

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