Traffic characterization and LTE performance analysis for M2M communications in smart cities

F. Malandra, L.O. Chiquette, L.-P. Lafontaine-Bédard, B. Sansò

G–2017–110
December 2017
Revised: May 2018

The series Les Cahiers du GERAD consists of working papers carried out by our members. Most of these pre-prints have been submitted to peer-reviewed journals. When accepted and published, if necessary, the original pdf is removed and a link to the published article is added.


Before citing this technical report, please visit our website (https://www.gerad.ca/en/papers/G-2017-110) to update your reference data, if it has been published in a scientific journal.

The publication of these research reports is made possible thanks to the support of HEC Montréal, Polytechnique Montréal, McGill University, Université du Québec à Montréal, as well as the Fonds de recherche du Québec – Nature et technologies.

Legal deposit – Bibliothèque et Archives nationales du Québec, 2018
– Library and Archives Canada, 2018

La collection Les Cahiers du GERAD est constituée des travaux de recherche menés par nos membres. La plupart de ces documents de travail a été soumis à des revues avec comité de révision. Lorsqu’un document est accepté et publié, le pdf original est retiré si c’est nécessaire et un lien vers l’article publié est ajouté.


Avant de citer ce rapport technique, veuillez visiter notre site Web (https://www.gerad.ca/fr/papers/G-2017-110) afin de mettre à jour vos données de référence, s’il a été publié dans une revue scientifique.

La publication de ces rapports de recherche est rendue possible grâce au soutien de HEC Montréal, Polytechnique Montréal, Université McGill, Université du Québec à Montréal, ainsi que du Fonds de recherche du Québec – Nature et technologies.

Dépôt légal – Bibliothèque et Archives nationales du Québec, 2018
– Bibliothèque et Archives Canada, 2018

GERAD HEC Montréal
3000, chemin de la Côte-Sainte-Catherine
Montréal (Québec) Canada H3T 2A7

Tél.: 514 340-6053
Téléc.: 514 340-5665
info@gerad.ca
www.gerad.ca
Traffic characterization and LTE performance analysis for M2M communications in smart cities

Filippo Malandra $^a$
Laurent Olivier Chiquette $^b$
Louis-Philippe Lafontaine-Bédard $^b$
Brunilde Sansò $^c$

$^a$ GERAD & Department of Electrical Engineering, Polytechnique Montréal, Montréal (Québec), Canada
$^b$ Department of Computer Engineering, Polytechnique Montréal, Montréal (Québec) Canada
$^c$ GERAD & Department of Computer Engineering, Polytech-
nique Montréal, Montréal (Québec) Canada

filippo.malandra@polymtl.ca
brunilde.sanso@polymtl.ca
Abstract: The paper presents a model for the characterization of Machine-to-machine (M2M) traffic and the performance evaluation of LTE access to support M2M communication, embedded into a web-based application. The application enables the study of the traffic produced by realistic M2M elements in the context of smart cities. Packet generation for each machine is modelled by means of three mathematical distributions (Poisson, Beta, and Deterministic), which makes it possible to represent a wide variety of M2M applications. A case study was constructed based on the city of Montreal. Real data on the position of machines were retrieved from public datasets. The case study includes a realistic representation of the LTE infrastructure that allows the estimation of traffic load at each eNodeB, as well as other performance indexes, such as collision probability and access delay. The use of real geographic information enables visual analyses aiming at identifying bottlenecks and possible roadblocks to the M2M integration in the LTE infrastructure.

Keywords: IoT, internet of things, traffic characterization, performance analysis, LTE
1 Introduction

M2M communications are usually referred to as the transmission of information among smart objects (i.e., devices with communication capabilities), without any human intervention. The importance of this kind of communication has risen in the last decade, thanks to the steep increase in the number of devices that are able to autonomously communicate with each other. The growth will accelerate in the next future, and the number of communicating devices is expected to rise to several billions in 2020. The connection of this large amount of communicating objects, also known as Internet of Things (IoT), needs to be supported by one of the existing communication infrastructures. LTE is currently seen as one of the best candidates due to its ubiquitous access and large spectrum availability. Moreover, 3GPP has - in Release 13 in 2014 - proposed Narrow Band IoT (NB-IoT), a new LTE-protocol specifically conceived to provide low power access to a large number of devices. The small transmission power and the reduced bandwidth (i.e., 200 kHz), makes NB-IoT particularly suitable for M2M communications.

The LTE infrastructure was, however, originally conceived to support human traffic, that is sensitively different from M2M traffic. First of all, M2M traffic is mostly in the uplink direction, whereas Human Type Communications (HTC) are most frequently distributed in the downlink. Second, the packet size in M2M applications is essentially in the order of hundreds of bits, considerably smaller than in HTC. Third, M2M devices are predominantly\(^1\) installed in fixed locations and do not require mobility, which is often needed in HTC. Moreover, human traffic is strongly correlated to the human activity time (e.g., busy during the day and sleeping at night), whereas that is not necessarily the case for machines activity times.

Finally, the cellular infrastructure - in particular the location and the settings of the base stations - is customized around the expected human position. This is why, for example, base stations are closer to each others in crowded urban areas and further apart in rural areas where the presence of humans is not very prominent. For all these reasons, M2M traffic needs to be thoroughly studied and the suitability of LTE, as well as other candidate solutions, needs to be assessed through customized performance evaluations.

LTE is basically composed of the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC). The E-UTRAN is supposed to be the segment which will be majorly affected by the introduction of massive M2M traffic. The resource scheduling in the uplink is based on an initial random access with a limited number of frequency slots to be used: this capacity might be the bottleneck when a large number of concurrent devices try to access the network. It is therefore important to assess whether the E-UTRAN is able to manage the traffic generated by M2M applications.

To examine this problem, we propose a web-based framework that can be used to characterize M2M traffic and study the suitability of standard LTE access mechanisms for massive M2M communications. The framework takes into account real geographic data on the position of machines, retrieved from public online databases. The traffic generated by realistic M2M applications is represented by means of three types of mathematical distributions (e.g., Poisson, Beta, and Deterministic). A network simulator was also implemented using Java to model the LTE random access procedure evaluating its performance. The proposed framework permit to visually analyze the performance of the LTE infrastructure, when simultaneously supporting multiple realistic M2M applications.

The remainder of this document is structured as follows: Section 2 contains a brief overview of the literature about M2M traffic characterization and performance analysis over LTE; Section 3 describes the implemented web application; Section 4 presents a case study with some numerical results; Section 5 contains the conclusions of this work.

2 State of the art

A good survey on the state of the art of M2M traffic issues over LTE can be found in [1]. The authors provide an accurate overview of the LTE network, pointing out the specific issues related to a massive integration of M2M communications. They also present an overview of the M2M traffic models proposed in

\(^1\)There are cases of M2M communications with mobile nodes (e.g., cars) but are not in scope in this work.
the current literature, and of access techniques anticipated in the LTE standard in order to cope with M2M communications strict requirements.

The use of LTE as supporting communication infrastructure for M2M traffic was first advocated by 3GPP in [2]. The authors provided a first attempt to model M2M traffic, proposing two models: (i) a uniform distribution for uncoordinated machines and (ii) Beta distribution for coordinated packet generation. Simple use cases were analyzed in which the packet collision probability was plotted against a varying number of machines. No background human traffic was considered. The collision probability was computed as the number of collisions over the total number of Random Access Opportunities (RAOs). However, it was later proved (e.g., in [3]) that this way to compute the packet collision probability leads to inaccurate results. The authors in [3] also showed that packet collision probability should be computed as the number of collisions over the total number of attempts.

One of the main issues with M2M traffic is the lack of a standardized characterization. Current approaches are subdivided in aggregated traffic and source-based models. The former, used for example in [4, 5], models all the machines as a single source; the correlation between the traffic of different machines is not taken into account. The latter is based on the fact that each machine is a separate entity and can generate traffic according to different set up parameters. This approach permits considering the traffic generation of one machine in relation to all the others. The first approach is computationally efficient and permits a smooth scalability since its complexity does not depend on the number of machines. On the other hand, source-traffic models provide more accurate results, but have a quadratic complexity on the number of machines and are practically unfeasible for large systems. An intermediate approach was proposed in [6], where a source traffic is adopted but with a lower complexity using a single background process to correlate traffic generation of different machines.

M2M traffic on LTE can also be characterized by using traces of mobile traffic, as was done in [7]. The authors analyzed a large amount of mobile data traffic provided by a US mobile operator, and were able to retrieve the traffic produced by machines by using the Type Allocation Codes of a selected set of communicating machines. This approach, although very realistic and accurate, relies on the use of traces of traffic, which are not widely available to the researcher community.

Differently from what was done in previous literature, in [8] real data on the position of machines were employed in order to characterize the traffic produced by realistic M2M applications at each eNodeB. The estimated position of machines was used to determine with more accuracy the number of machines associated to each eNodeB. In the paper at hand, we build upon what was done in [8] by also considering several performance indexes of the LTE access (e.g., collision probability, and access delay), along with traffic measures, such as data volume and number of packets. We also introduce the details of the geographic web application where the traffic simulation is embedded.

3 The web application

The architecture of the web application at hand is shown in Figure 1. The proposed framework encompasses three building blocks: (i) the geographic database, (ii) the M2M application definition, and (iii) the network simulator. As one can notice, the third block is further divided into traffic generation and LTE access performance evaluation. Each of these units are separately described in what follows.

3.1 Geographic database

As previously stated, contrary to human behavior, most machines are not intended to move. Although the exact (or estimated) location of machines is often neglected in the current M2M literature, we believe that it is possible to gain a valuable insight into M2M traffic by analyzing where the communicating machines are installed. The geographic aspect of the problem is even more important when it comes to studying the congestion in the LTE access, for which it is fundamental to know the number of machines associated to each eNodeB. It is evident that this would not be possible without the knowledge of the position of the communicating machines.
In our case study, later presented in Section 4, we were able to retrieve the position of smart meters, traffic lights, bus stops, parking lots, traffic signs, security cameras and others from public databases.

### 3.2 M2M applications

A wide variety of M2M applications are currently implemented or will be in the near future. They can be identified by (i) the involved machines and by (ii) the communication traffic they generate. It is important to remark that one or multiple sets of machines can be assigned to a single M2M application (e.g., a monitoring application with sensors installed in traffic lights and bus stops), and also that several M2M applications can be assigned to the same set of nodes (e.g., smart meters can be used for meter reading, but also for building security). A comprehensive list of the M2M applications which are considered in this paper can be found in Section 4. Once the involved machines are chosen, it is important to characterize the traffic they generate.

In Figure 2, the parameter selection form of the web application at hand is shown. In the upper box, it is possible to define the parameters of the desired set of M2M applications to be included in the analysis, such as the name and the machine types; it is also possible to choose traffic-related parameters, such as packet size, and distribution type (discussed in Section 3.3). In the box at the bottom, it is possible to set all the details of a simulation, such as simulation starting state and time, time horizon, LTE time slot duration, and number of RAOs.

### 3.3 M2M traffic characterization

The traffic characterization of an M2M application amounts to finding a stochastic process that represents the packet generation over time for the machines involved. Three mathematical distributions are used to model the packet generation of single machines, as it can be seen in Figure 2: (i) Poisson, (ii) Beta, and (iii) Deterministic.

Poisson distribution is used when the packet generation of a machine is completely independent from the packet generation of other machines. A typical example is the smart metering application, in which smart meters transmit to the power utility the measured power consumption. The time distance between two consecutive transmissions of one single smart meter is exponentially distributed, with a mean parameter varying between few minutes and several hours. This distribution is widely adopted in M2M traffic characterizations because it is simple and permits to perform large scale analysis, as M2M networks require.

Beta distribution is employed to model the packet generation of a set of machines after an event that triggers the transmission of all the machines in the set. An example of such applications is the response of
seismic sensors to an earthquake in their vicinity: neglecting a possible malfunctioning, all the sensors that identify the earthquake event will send an alarm at a time instant which is between 0 and $T$ seconds after the earthquake, being $T$ a parameter of the Beta distribution. The Beta distribution depends on parameters $\alpha$ and $\beta$: $[2]$ and all the literature on M2M traffic characterization have assumed $\alpha = 3$ and $\beta = 4$ in their analyses. This assumption is also used in this paper, for consistency reasons.

Differently from Poisson and Beta, the Deterministic distribution is used to characterize the traffic of M2M applications whose machine produce packets at predetermined time instants. Suffice it to think of the public transportation application: a packet is transmitted whenever a bus arrives at a bus stop, an event that takes place at scheduled times. However, the mere use of scheduled times would not grasp the random nature of this process: a bus rarely arrives at the exact scheduled time $X$; instead, it arrives within a certain interval $X \pm \Delta X$. We called $\Delta$ the uncertainty parameter and gave the user the possibility to choose its value when dealing with Deterministic M2M applications in proposed web application.

### 3.4 LTE access performance

Once a set of M2M applications is chosen (see Section 3.2), and traffic is generated (see Section 3.3), it is necessary to study the performance of the LTE infrastructure used to carry this traffic. As anticipated, only the access part will be considered in this study since it is the one mainly expected to suffer from a large number of devices attempting to use LTE resources to transmit. In what follows, a brief overview of the LTE access procedure is provided.

In order to be associated to an eNodeB and transmit messages over LTE, a User Equipment (UE) needs to acquire the Physical Cell Identifier (PCI) signal, and synchronize with time-slots and frames transmitted by the eNodeB. After that, the UE can start the access procedure, which is illustrated in Figure 3. This procedure is needed whenever (i) a UE connects for the first time to a network, or (ii) attempts to restore a connection after a link failure, or (iii) moves to another cell, or (iv) updates its location, or (v) requests scheduling resources.

As one can see from Figure 3, the LTE access procedure is based on 4 steps and is originated by the UE. In the first step, the UE transmits a so-called preamble on the Physical Random Access Channel (PRACH). Preambles can be randomly chosen from a set of 64 orthogonal signals, and transmitted over a predefined number of slots, which are dedicated to the PRACH, generally referred to as PRACH opportunities. Hereafter, we denote with $\text{RAO}$ the total number of preambles multiplied by the PRACH opportunities. The random
access procedure to a given eNodeB is modelled as a multichannel Slotted ALOHA with a number of channels equal to the number of RAOs. Collision might occur when two or more UEs transmit the same preamble signal in the same slot; in other words, collisions happen when two or more UE use the same RAO. In Figure 4, we represented an example of the outcomes of an access procedure by means of a grid in which in the vertical axis we have the RAOs, and in the horizontal axis the set of time slots in the simulation. In each cell of the grid, we reported the number of attempts and we used green to identify successful transmissions, and red to represent collisions. Unused RAOs are left blank. In this example, a collision happens in two cases: at time slot 1 with two attempts to use RAO 2, and at time slot T, with two attempts to use RAO 3.

In Figure 2, two additional simulation parameters are shown: Random Access Response Window (RARW) and Backoff Indicator (BI). RARW represents the time that a UE waits after the transmission of a preamble: if no RA response is received within this time, the UE assumes a collision happened and will retransmit a new preamble. The time at which the UE attempts a new preamble transmission depends on the parameter BI (usually expressed in ms). In particular, the UE can transmit from 0 to BI ms after the expiration of RARW.
4 Case study: Montreal

Montreal, the second largest city in Canada, was chosen as case study for the proposed framework, available at www.trafficm2modelling.com. This city represents a good fit for what concerns M2M applications, because it was recently acknowledged as one of the top intelligent cities in the world in 2016 by the Intelligent City Forum (ICF). Publicly available data on the position of several machine types in Montreal are provided, as well as the LTE infrastructures of several providers. The proposed web application allows the user to create M2M applications tailored to his or her needs, by tuning traffic and simulation parameters. However, hereafter we present an analysis based on a predefined set of six M2M applications, used to show the capabilities of the framework under study. In what follows, we present (i) the features of the six realistic M2M applications and the data on the position of machines in the area of Montreal, (ii) the realistic LTE infrastructure used in the study, and (iii) numerical results on the traffic characterization and on the performance analysis of the system at hand.

4.1 M2M applications under study and related machine data

We decided to include in our analysis the following M2M applications:

**Smart metering:** the transmission of small packets from smart meters, located at residential dwellings, to the power utility metering data management system. A Poisson distribution with mean parameter equal to 1 hour and packet size of 200 Bytes is considered. Data on residential addresses from [9].

**Traffic monitoring:** the transmission of traffic reports generated by sensors installed in traffic lights. The average transmission time might be from as little as few seconds (for real-time applications) to few minutes (where a more delay-tolerant analysis is sought). In this study, we used a Poisson distribution with a mean generation time of 5 s and a packet size of 500 Bytes. Data on traffic lights from [10].

**Public transportation:** a packet is transmitted from a bus stop whenever a bus arrives. This permits the public transportation provider to have real-time updates on the position of the buses in its fleet, and also to provide the customers at a bus stop with a consistent estimation on the time of arrival of the next buses. We retrieved one profile for working days and one for weekends and holidays. A deterministic traffic distribution is employed with a packet size of 300 Bytes. Public transportation data from [11].

**Smart parking:** the transmission of packets from sensors installed at parking lots. This information can be used to manage and enforce the payment of parking fees, to deal with special permits for residents, or to help users in finding an available parking spot. A Poisson distribution with a mean parameter of 30 minutes and a packet length of 250 Bytes was used. Data on parking spots are available at [12].

**Public safety:** security cameras are installed in selected locations throughout a city. They can transmit captured pictures or videos either at random time instants, or as triggered by events (e.g., a car accident). A Poisson distribution was used with 2 MB transmitted each minute. Data on security cameras are available at [13].

**Smart meter - Beta:** in some occasions, the power utility might need to have all the smart meters in a certain area transmit (e.g., to define the boundaries of an outage, or to check if a power outage event was solved throughout the city). The simultaneous transmission of all the machines, following one of the aforementioned events is modelled using a Beta distribution between 0 and 30 s after the event. The occurrence of Beta events is assumed to be Poisson distributed with an average of 2 events per day.

4.2 LTE infrastructure

A realistic LTE infrastructure was used to support M2M communications in our case study. A comprehensive database with the position of all installed eNodeB stations in Canada was found from [14]. Data were filtered in order to retrieve the eNodeB stations used by each operator in the area of Montreal; the position of the base stations is then used to produce a Voronoi diagram to subdivide the area of Montreal. Illustrated in Figure 5 is the Voronoi diagram when the LTE infrastructure of Rogers, that has 544 eNodeB stations, is selected. The number of RAOs per frame assumed for this case study is 54, and no human traffic is added to the analysis. The duration of frames is equal to 10 ms, as per LTE specifications.
4.3 Numerical results

A 24-hour simulation was performed with the six M2M applications defined in Section 4.1. The total computational time using a processor Intel(R) Core(TM) i7-4770 CPU @ 3.40GHz was 4 minutes and 34 seconds.

In Table 1, we reported the values of four indexes (i.e., data volume, packet count, collision count, and collision probability): in the last row, we have values for the whole simulation; in the others, we reported values for the six considered applications. The total M2M traffic produced was of 1.141 TB, mainly generated by the public safety application, with 1.125 TB (i.e., the 98.6% of the total data volume). Moreover, 41634928 packets were transmitted. The traffic monitoring application was the one generating the largest number of packets (31055695, amounting to the 74.5% of the total generated packets). The highest number of collisions and collision probabilities corresponds to the Smart metering Beta traffic: the Beta distribution, as discussed in Section 3.3, produces a large number of packets in a limited time span, which can increase the chances of a packet collision.

<table>
<thead>
<tr>
<th>M2M Application</th>
<th>Data Volume</th>
<th>Number of Packets</th>
<th>Collision count</th>
<th>Collision Prob. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart Metering</td>
<td>1.499 GB</td>
<td>8046807</td>
<td>1933</td>
<td>0.02</td>
</tr>
<tr>
<td>Smart Metering (beta)</td>
<td>63.925 MB</td>
<td>335151</td>
<td>10572</td>
<td>3.06</td>
</tr>
<tr>
<td>Smart Parking</td>
<td>214.614 MB</td>
<td>900155</td>
<td>194</td>
<td>0.02</td>
</tr>
<tr>
<td>Public Transportation</td>
<td>194.132 MB</td>
<td>678539</td>
<td>163</td>
<td>0.02</td>
</tr>
<tr>
<td>Public Safety</td>
<td>1.125 TB</td>
<td>618581</td>
<td>167</td>
<td>0.03</td>
</tr>
<tr>
<td>Traffic Monitoring</td>
<td>14.461 GB</td>
<td>31055695</td>
<td>8909</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.141 TB</strong></td>
<td><strong>41634928</strong></td>
<td><strong>21938</strong></td>
<td><strong>0.05</strong></td>
</tr>
</tbody>
</table>

In Figure 6, we reported a heat-map of Montreal for the following three indexes: (i) data volume (see Figure 6a), (ii) number of packets (see Figure 6b), and (iii) collision probability (see Figure 6c). The colour of each zone is related to the three aforementioned indexes according to the colour-bar at the top left of each figure: white is used for the minimum, and black for the maximum value. In Figure 6a, it is possible to observe that the largest amount of traffic (dark grey coloured) is concentrated where the security cameras are installed. A different situation is shown in Figure 6b: on top of the packets produced by security cameras, there are many other machines producing a high number of packets, resulting in a heat-map with more zones coloured in dark grey, with respect to 6a. In Figure 6c, we can notice that high collision probabilities are observed in LTE cells not highlighted in the heat-map showing the packet count. These cells are characterized by a high number of houses, and are therefore majorly affected by the Smart metering - Beta application, that leads to a high number of collisions.
It is also important to remark that the design of the LTE infrastructure has an impact on the performance of M2M traffic. In fact, in the downtown area LTE cells are considerably smaller than in the rest of the city, in order to serve an expected high number of humans. However, these cells do not contain a high number of machines; therefore, in the downtown area we observe an oversized allocation of LTE resources, with respect to M2M traffic. On the other hand, other LTE cells (especially in the less crowded west part of the city) have a larger size, as highlighted in Figure 6, which leads to a higher concentration of machines and a lower performance.

5 Conclusions

This work focused on the M2M traffic characterization and on the performance evaluation of the LTE access to support massive M2M communications. A web-application was implemented for this study, and is publicly available at www.trafficm2modelling.com.

The web-application allows to consider the exact position of different sets of machines (e.g., traffic lights, smart meters, bus stops). The exact or estimated geographic position permits to increase the fidelity of studies to actually implemented M2M systems. The generation of traffic of each machine is modelled by means of three mathematical distributions: Poisson and Beta, which were already considered by previous literature, and a Deterministic distribution, which was adopted to represents M2M applications that generate
packets according to a predetermined scheduling technique. A network simulator was implemented and allows to reproduce the operation of the LTE access and to compute the collision probability and the access delay of M2M packets.

The web application is flexible, and permits the user to tune both traffic and simulation parameters in order to customize the analyzed M2M applications to his or her needs.

The M2M traffic characterization and performance analysis was applied to Montreal, one of the top intelligent cities, according to the ICF in 2016. The case study was built using publicly disseminated data on the position of machines. Six realistic M2M applications were simultaneously considered in the presented results.

An LTE infrastructure is represented using publicly available information on the position of eNodeB stations in Canada. The location of LTE base stations was used to subdivide the metropolitan area at hand in sub-regions. This permits to estimate the traffic load at each eNodeB in the topology, as well as to carry out global analyses on the aggregation of traffic for the whole city of Montreal.

Numerical results are reported to show the capabilities of the proposed framework, and the type of analyses that is possible to carry out. A comparison of the performance indexes of different M2M applications is presented in order to highlight their peculiarities. Heat-maps are reported showing how the performance varies in different areas of the city: this analysis highlights some differences between M2M and human traffic in the LTE infrastructure.

References