Impact of M2M Communications on Cellular Telecommunications Networks

Modeling the effects of M2M Communications on Cellular Core Networks

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Abstract — **Machine to Machine (M2M) communications have experienced very fast growth in recent times and several forecasts indicate that this trend is going to increase dramatically over the coming years. The traffic generated by M2M services can have very different characteristics as compared to conventional data or voice traffic, heavy burstiness being one its main features. This paper addresses the above issues in the context of cellular networks. Models for signaling and payload throughput in cellular core networks are derived, with particular focus on the effects of aggregated M2M services. These models were implemented in a computational tool that provides visualization of network performance and capacity metrics as function of different service orchestrations. This can be of great usefulness for Mobile Network Operators (MNOs) and other entities that need to understand how to design M2M services and how to deal with their impacts on cellular networks.**

Keywords-Access Networks; Cellular Networks; Core Networks; Internet of Things; M2M; Mobile Networks; Network Planning; Service Orchestration; Traffic Analysis; UMTS.

I. Introduction

Telecommunications services are on the verge of major changes with the rising of Machine to Machine communications and the Internet of Things (IoT). It is expected a growth on the number of connected devices up to 50 billion by 2020 [1]. Such numbers might still be a few years away, but many M2M services are starting to roll out [2].

The effects that M2M related traffic will imply to cellular networks are widely unknown and unstudied, thus it becomes the fundamental objective of this paper to provide models that can be of usefulness to understand such effects, to provide insights on how to design M2M services, and to study the changes that must be enforced on cellular networks.

The focus on cellular networks, is justified by considering that this access technology is the only that can guarantee extremely high rates of coverage. Thus, it is believed that cellular infrastructures are going to be fundamental in the roll-out of services based on M2M technologies.

Additionally, it is expected that traffic generated by many M2M services will present similar characteristics to traffic generated by modern smartphone applications, mainly social networks and instant messaging applications [3]. Thus, this work is believed to be of relevance to services other than M2M.

The traffic generated by M2M services will present very different features when compared to conventional data and voice traffic. Such features will include different patterns of use, with some services presenting high predictability, and others high unpredictability. Many M2M services will generate data transmissions very few times a day, others, a high number of transmissions with very small payloads [4][5]. Burstiness, a statistics concept that refers to the intermittent increases and decreases in the activity or frequency of an event, will also be a typical characteristic for most M2M generated traffic [4][6].

Considering that cellular networks have not been design to deal with this kind of traffic, it becomes urgent to understand how a broad adoption of M2M services will affect the cellular networks. Particularly, considering the number of sessions, the number of subscriptions, and the amount of signaling generated by very small quantities of payload information. Such understanding will provide MNOs with the necessary knowledge to redesign and resize their cellular networks as well as design M2M services, applications, and platforms.

This paper is comprised by eight sections. Section I presents an overview on the problem at study. Section II presents some of the main implications of M2M Communications on Cellular Telecommunications Networks. Section III proposes a model for Universal Mobile Telecommunications System (UMTS) Packet Core (PC) traffic and throughput analysis. Section IV proposes a model for UMTS PC network modeling. Section V proposes a model for service orchestration. Section VI describes a computational tool developed in order to apply the previously referred models. Section VII presents a case study, illustrative of the application of the proposed models, and finally, Section VIII presents the conclusion and discussion, as well as future work on this subject.

II. Impact of M2M Communications into Cellular Networks

Current core network architectures are designed mainly for Human to Human communication, and are not prepared to deal with the foreseeable increase on signaling traffic. Such increase is driven by the growth on M2M and smartphone signaling traffic (growing 50% faster than data traffic [3]). Furthermore, the overall impacts on network capacity and performance, caused by adding a large number of M2M subscriptions to current networks are generally unknown, and may require new levels of scalability, in terms of subscription handling and in terms of mobility and resource management [7]. Considering the explosion of M2M communications, and given that designing a system based on the worst case is very costly [8], it is important to design models and algorithms to depict the networks on large M2M deployment scenarios, allowing for its dimensioning based on average values with some kind of overload control strategies.

Some M2M related factors that might have impact on Core Network performance are:

A. M2M Traffic Temporal Regime

M2M communications present a broad number of applications and services. Thus, is no surprise that the M2M traffic temporal regime can be very heterogeneous among different applications and usage scenarios, and consequently its characteristics are diverse and hard to predict. This is a fundamental difference from most Circuit Switched (CS) traffic, adding up to the complexity of analysis of this issue.

B. Burstiness

Burstiness is a statistics concept that refers to the intermittent increases and decreases in the activity or frequency of an event, which is characteristic of most of M2M related traffic [4][6]. Understanding the burstiness behavior of data traffic is fundamental, since burstiness introduces sudden peak loads to the network, and is relevant for design and QoS purposes [8]. One of the fundamental design issues related to burstiness is to determine which solution is better: to have devices always in Packet Data Protocol (PDP) active state or to have them constantly activating and deactivating PDP sessions.

C. Relation between information payloads and signaling overheads

One of the implications of such decision is on the payload to signaling ratio. Sessions being constantly activated and deactivated will increase dramatically this ratio, with consequences that are not yet known. Some of them might be congestion on elements/functions, such as Authentication, Authorization and Accounting (AAA), Gateway GPRS Support Node (GGSN), Online Charging System (OCS) and Serving GPRS Support Node (SGSN).

D. Addressability

On the other hand, if every single device is always with an active PDP session there will be a need for more IP addresses, and probability an expansion on several databases such as Home Location Register (HLR) and Authentication Center (AuC). Such a scenario could require the deployment of IPv6, since IPv4 would not sustain such a network for a long period.

III. TRAFFIC AND THROUGHPUT ANALYSIS FOR UMTS PACKET CORE NETWORKS

The presented work will now focus on UMTS networks, but it can be applicable to other 3GPP technologies. In order to identify the elements and interfaces of the 3G network whose performance and capacity are most critically exposed to negative effects of M2M traffic, a set of models has been developed to calculate payload and signaling throughput on a UMTS network. The following sections present models for Iu-Packet Switched (PS) and Gr interface.

A. Iu-PS Interface

The "Iu" interface is comprised of two connections, the Iu-PS interface that interconnects the Radio Network Controller (RNC) and the SGSN and the Iu-CS interface that connects the RNC to the Media Gateway (MGW). The MGW is part of the CS domain and therefore the Iu-CS interface will not be considered in the following calculations (M2M communications will be supported by the Packet Core). Adapting the work presented in [8][9], the following equations can be formulate:

1) The overhead ratio in Iu-PS interface is given by:

$$RO_{Iu-PS} = \frac{S_{Packet} + H_{IuUP} + H_{GTP} + H_{UDP} + H_{IP} + H_{MPLS}}{S_{Packet}}. \quad (1)$$

where:

- "S_{Packet}" is the average IP packet size [bytes];
- "H_x" is the header size of "x" packet, as depicted on Table I [bytes].

TABLE I. PROTOCOL STACK OF IU-PS INTERFACE - BASED ON [8][9]

Radio Network Control Plane			PS Data Plane	Header Size	OSI model
RANAP			Iu-UP	HIu-UP	layer 4, Transport
SCCP					
MTP3-B	SCTP		GTP-U	HGTP	
SSCF-INI	IP		UDP / TCP	HUDP	
SSCOP			IP	HIP	3, Network
MPLS			MPLS	HMPLS	2, Data Link
layer 1, Physical					

2) The throughput of data plane in the Iu-PS interface (expressed in bps) is given by:

$$TH_{UP_{IuPS}} = N_N * R_{Attach} * R_{\frac{Active}{Attach}} * Th_{Node} * RO_{Iu-PS} * f_d. \quad (2)$$

where:

- "N_N", "R_{Attach}", "$R_{\frac{Active}{Attach}}$", and "$Th_{Node}$" are defined on Table IV;
- "RO_{Iu-PS}" is the overhead ratio in Iu-PS interface, given by (1);
- "f_d" is the data throughput redundancy factor.

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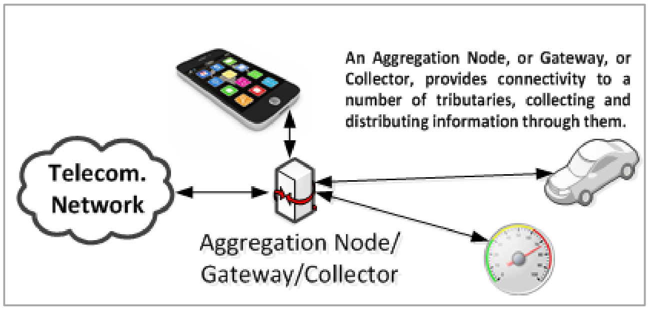

Figure 1. Aggregation Node (AN) definition.

Table II lists eleven basic types of messages that can be estimated by MNOs and that comprise most of the throughput in control plane of Iu-PS interface.

TABLE II. FOOTNOTES FOR (3) - BASED ON [8][9]

i	N_{IuPS_i}	L_{IuPS_i} [bits]	Relevant for M2M comm.
1	Authentication times per hour	Length of messages per authentication	yes
2	Attachment times per hour	Length of messages per attachment	
3	Detachment times per hour	Length of messages per detachment	
4	Inter SGSN route update times per hour	Length of messages per inter SGSN route update	only if M2M service requires mobility
5	Intra SGSN route update times per hour	Length of messages per intra SGSN route update	
6	Intra SGSN Serving Radio Network Subsystem (SRNC) route update times per hour	Length of messages per intra SGSN SRNC	
7	PDP activation times per hour	Length of messages per PDP activation	yes
8	PDP deactivation times per hour	Length of messages per PDP deactivation	
9	Periodic SGSN route area update times per hour	Length of messages per periodical SGSN route update	
10	SMS mobile originated times per hour	Length of messages per SMS service	only if M2M service requires SMS
11	SMS mobile terminated times per hour		

3) Thus, the signaling load of Iu-PS interface (expressed in bps) is given by:

$$S_{IuPS} = N_N * R_{Attach} * \sum_{i=1}^{11}\left(N_{IuPS_i} * L_{IuPS_i}\right) * \frac{1}{3600} * f_s. \quad (3)$$

where:

- "N_{IuPSi}" is given by Table II;
- "L_{IuPSi}" is given by Table II;
- $\frac{1}{3600}$ is used to convert hours to seconds;
- "f_s" is the signaling throughput redundancy factor.

Table II messages comprise the signaling of Iu-PS interface. Messages such as P-Temporary Mobile Subscriber Identity re-allocation message, identification check message, and service request message are not considered in (3) due to their small size and reduced usage. If proven necessary to integrate them into the Equation, a redundancy factor can be imposed (f_s). The number of periodic Route Area Updates (RAUs) is determined by:

$$N_{Route_{periodic}} = \frac{N_N\,(1-R_{Active})}{P_{Refresh}*3600}. \quad (4)$$

where:

- "$P_{Refresh}$" is the periodic RAU interval [s];
- 3600 is used to convert seconds to hours;
- "$N_N\,(1-R_{Active})$" is the number of idle ANs.

B. Gr interface

Applying the same method is possible to define the signaling load going through Gr interface (expressed in bps):

$$S_{Gr} = N_N * R_{Attach} * \sum_{i=1}^{3}\left(R_{Gr_i} * N_{Gr_i} * L_{Gr_i}\right) * \frac{1}{3600} * f_s. (5)$$

where:

- "R_{Gri}" is given by Table III;
- "N_{Gri}" is given by Table III;
- "L_{Gri}" is given by Table III.

TABLE III. FOOTNOTES FOR (5) - BASED ON [8][9]

i	R_{Gr_i}	N_{Gr_i}	L_{Gr_i} [bits]	Relevant for M2M
1	Authentication Rate	Authentication times per hour	Length of messages per authentication	yes
2	Attach Rate	Attach times per hour	Length of messages per attachment	
3	not applicable	Inter SGSN route update times per hour	Length of messages per inter SGSN route update	only if requires mobility

The same methodology can be applied to other UMTS PC interfaces.

IV. UMTS PACKET CORE NETWORK MODELING

Using the throughput models from the previous section it is possible to design a mathematical model of the throughputs and capacity of an UMTS PC Network.

In order to study such network, let us consider the model presented on Figure 2, where:

- "w_i" is the raw throughput capacity for interface "i" [bps];
- "SIG_{i_x}" is the signaling capacity for interface "i" of Network Element (NE) "x" [bps];
- "w_{i_x}" is the raw throughput capacity for interface "i" of NE/System "x" [bps].

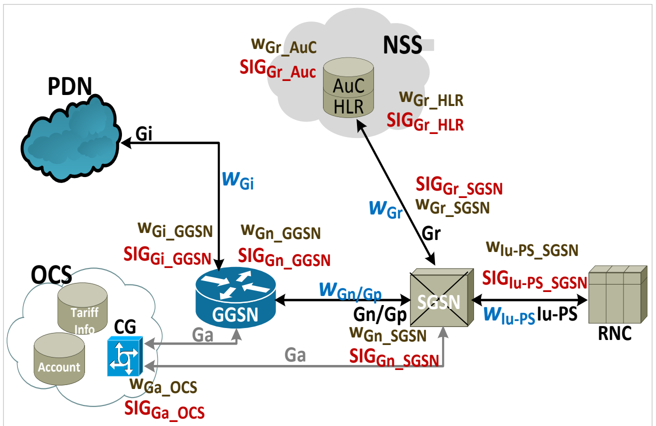

Figure 2. Mathematical description for the UMTS Packet Core Network model.

This model is useful in order to develop a computational tool capable of applying the models proposed in Section III.

V. SERVICE ORCHESTRATION

The traffic models presented in previous sections require knowledge about the aggregated M2M traffic coming from the user side. This section presents an orchestration model capable of providing an approximation for this aggregated traffic as function of different usage profiles.

Table IV presents the variables that must be defined for each service to consider on the orchestration operation.

TABLE IV. PARAMETERS FOR SERVICE ORCHESTRATION

Variable	Symbol	Description
Number of connections	N_N	Number of subscriber devices (Smartphones, ANs, Cars, etc).
Throughput	Th_{Node}	Node throughput (aggregated throughput of several tributaries) [bps].
Sessions / Hour	N_{IuPS_7}, N_{IuPS_8}, N_{Gni}	Number of service sessions per hour; Correspondent to the number of PDP activation / deactivation requests.
Attachments / Hour	N_{IuPS_2}, N_{IuPS_3}, N_{Gr_2}	Number of attachment times per hour; Considered to be correspondent to the number of detachment times per hour.
Authentications / Hour	N_{IuPS_1}, N_{Gr_1}	Number of authentication operations per hour.
Intra SGSN route updates / Hour	N_{IuPS_5}, N_{IuPS_6}	Number of Intra SGSN and Intra SGSN SRNC route update times per hour.
Inter SGSN route updates / Hour	N_{IuPS_4}, N_{Gr_3}	Number of Inter SGSN route update times per hour.
Periodic SGSN RAUs / Hour	N_{IuPS_9}	Number of periodic SGSN RAU times per hour.
Authentication Rate	R_{Gr_1}, $R_{auth_{HLR}}$	Ratio of authentication that needs to get parameters from HLR [%].
SMSs MO / Hour	$N_{IuPS_{10}}$	Number of SMSs Mobile Originated per hour.
SMSs MT / Hour	$N_{IuPS_{11}}$	Number of SMSs Mobile Terminated per hour.
Premium Subscr. Ratio		Ratio of premium subscribers. [%].
Regular Subscr. Ratio		Ratio of regular subscribers [%].
Basic Subscr. Ratio		Ratio of basic subscribers [%].
Attached Subscribers Ratio	R_{Gr_2}, R_{Attach}	Ratio of attached subscribers [%].
Active/Attached Subscribers Ratio	$R_{\frac{Active}{Attach}}$	Ratio of attached subscribers with active session [%].

The node throughput is given by the sum of the several tributaries/services throughputs:

$$T_{node} = \sum Th_k. \quad (6)$$

where:

$$Th_k = \frac{\delta}{t_\delta + t_t}. \quad (7)$$

$$t_t = N_{Packets} * t_{bP}. \quad (8)$$

$$N_{Packets} = \frac{\delta}{P_{size}}. \quad (9)$$

where:

- "Th_k" is the throughput generated by the service "k" [bps];
- "δ" is the average size of the data message to be transmitted [bits];
- "t_δ" is the time between data messages transmissions [s] (see Figure 3);
- "t_t" is the time of transfer [s] (see Figure 3);
- "$N_{Packets}$" is the number of packets needed to transfer the required data;
- "t_{bP}" is the mean time between Packets within a Packet burst [s] (see Figure 3);
- "P_{size}" is the average packet size [bits].

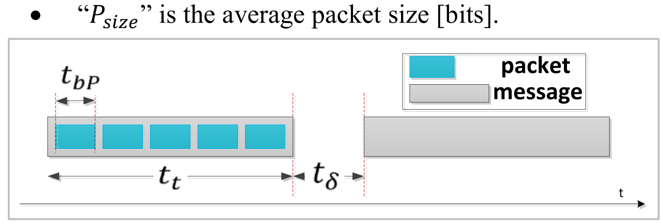

Figure 3. Equation (7) and (8) time relationships.

Equations (7) to (9) are adapted from [10].

VI. COMPUTATIONAL TOOL

In order to provide a visualization and interactive environment based on the previously presented models, a computational tool has been developed with the objective of calculating and providing visual representations of network behavior as a function of different service orchestrations. The tool flowchart is depicted on Figure 4.

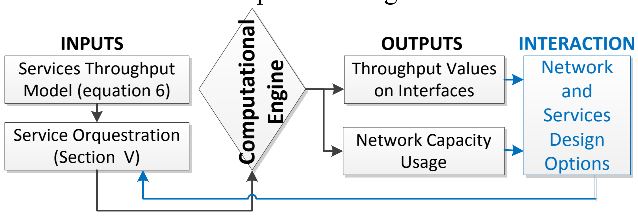

Figure 4. Computational tool flowchart.

Although this paper studies UMTS, this tool can be applicable to other 3GPP technologies.

VII. CASE STUDY

A. *Example of Application*

To illustrate the applicability of proposed models, let us consider a case study where it will be studied the uplink capacity usage of Iu-PS and Gr interfaces as a function of M2M services usability. Let us consider a UMTS network with the following characteristics:

- $w_{Iu-PS} = w_{Iu-PS_{SGSN}}$ = 100.000 Mbps;
- $w_{Gr} = w_{Gr_{SGSN}}$ = 500 kbps.

The service orchestration is based on the following elements:

- Baseline service set (CS and PS services already present in the network before the introduction of M2M services);
- M2M service set (e.g., Smart Metering, Home Automation, Healthcare, Security, etc.).

In order to calculate the capacity usage prior to considering M2M services, i.e. the baseline service set, the model described in equations (6) to (9) will be applied to the various services under consideration (PS services such as browsing, email, social networks, streaming, etc., and PS services such as voice calls and Short Message Service (SMS)). As an example of the method applied, calculations for email are presented on Table V.

Let us now consider that replicating these calculations for other services, and considering that 100,000 cellular subscribers (assumed to be, mainly, smartphone subscribers) are being served, the values for Iu-PS and Gr baseline usage (uplink) can be calculated [11] and will provide the following values:

- Iu-PS usage baseline: 105 Mbps (of which, 3% is signaling);
- Gr usage baseline: 350 kbps (of which, 100% is signaling).

TABLE V. EMAIL PROFILING

	Downlink	**Uplink**
Average size of message (δ)	75,00 Kbytes	20,00 Kbytes
Average Packet size (P_{size})	800 bytes	800 bytes
Number of Packets ($N_{Packets}$)	93,75	25,00
Mean time between Packets within burst (t_{bP})	0,015 s	0,015 s
Time between data message transmissions (t_{δ})	1200 s	1200 s
Time of transfer (t_t)	1,41 s	0,38 s
Email throughput (Th_{email})	0,50 kbps	0,27 kbps

TABLE VI. M2M SERVICE ORCHESTRATION

M2M service	Smart Metering	Healthcare	Automotive	Public Transportation	Security
N_N	50.000	50.000	50.000	1.000	10.000
Th_{Node} [kbps]	0,50	1,00	0,50	0,50	1,00
S_{packet} [bytes]	130	130	130	130	130
N_{Attach}	2,00	13,42	0,42	60,00	8,00
N_{Detach}	2,00	13,42	0,42	60,00	8,00
$N_{PDP_{activation}}$	2,00	13,42	0,42	60,00	8,00
$N_{PDP_{deactivation}}$	2,00	13,42	0,42	60,00	8,00
$N_{SRNC_{intra-SGSN}}$	0,00	0,03	0,07	1,00	0,10
$N_{SRNC_{inter-SGSN}}$	0,00	0,01	0,03	0,01	0,01
$R_{auth_{HLR}}$	20%	20%	20%	20%	20%
$N_{SMS_{MO}}$	0,00	0,00	0,00	0,00	0,00
$N_{SMS_{MT}}$	0,10	1,00	0,80	0,00	0,00
$R\frac{Up}{Total}$	100%	100%	100%	100%	100%
$f_{redundancy_{data}}$	1,10	1,10	1,10	1,10	1,10
$f_{redundancy_{signaling}}$	1,00	1,00	1,00	1,00	1,00
R_{Attach} , $R\frac{Active}{Attach}$	Please refer to Figure 5				

For sake of simplicity, it shall be considered that the baseline usage is constant through the 24 hours of the day.

The network at study will provide connectivity for a set of M2M services, which are considered to be as presented on Table VI and Figure 5.

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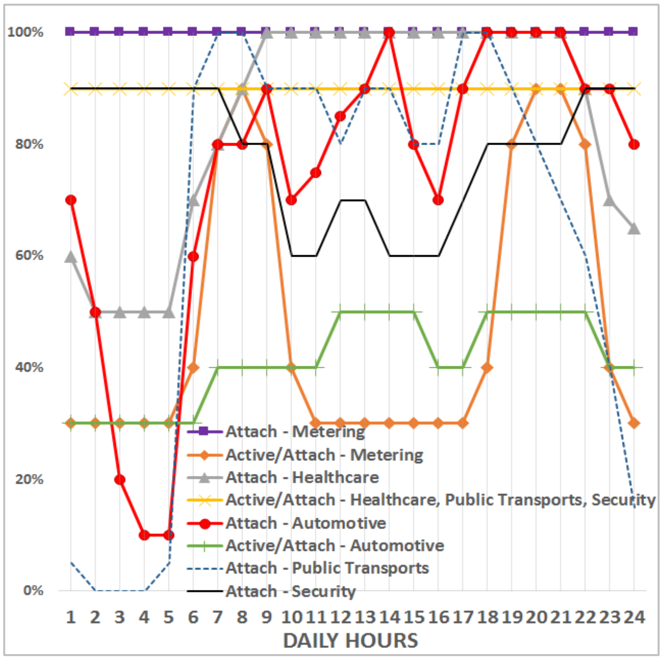

Figure 5. 24 Hourly usage profile for M2M services.

In order to apply the proposed models, the header size for the protocol stack of the interface Iu-PS must be known.

Assuming that header values for the Iu-PS interface are as presented on Table VII, and applying them to (1), it comes:

$$RO_{Iu-PS} = 1{,}40.$$

TABLE VII. HEADER SIZE FOR IU-PS INTERFACE - BASED ON [9]

User Plane	Header Size [bytes]
Iu-UP	4
GTP-U	12
UDP	8
IP	20
MPLS	8
Total	**52**

In order to apply (3) and (5), it is necessary to know the length of messages, which are considered to be as presented on [9].

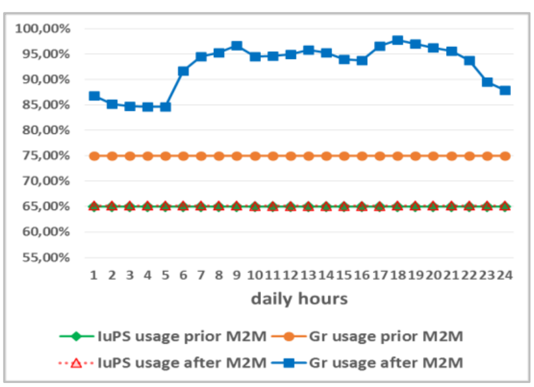

Figure 6. Case study results.

Now that every variable has been presented, it is possible to input the service orchestration parameters of Table VI into the computational tool, and visualize results. For this case study, the tool provides the results of Figure 6, which shows uplink usage rates (%) for the Iu-PS and Gr, prior and after the addition of M2M services.

By analyzing this figure, it can be concluded that the impact of M2M traffic on Iu-PS interface is negligible, since the payload generated by these M2M services is small, and the amount of signaling is small relatively to the capacity of this interface. However, on Gr interface it is visible a considerable increase on capacity usage, showing that M2M services have increased significantly the amount of control information being carried by this interface (HLR, AuC). In the scenario at study, after considering M2M services, Gr interface is dangerously close to its full capacity, which could originate network congestion and QoS/QoE degradation.

B. Sensitivity Analysis for Orchestration Parameters

An important feature provided by the developed tool is that it allows service developers to foresee how the network will respond as a function of service orchestration and parameterization scenarios. In order to identify which service parameters could be problematic to the network performance, a sensitivity analysis for the M2M service orchestration parameters is presented as a function of different interface usage ratios when varying a set of service orchestration parameters. To this purpose, the tool was configured to consider a M2M service, characterized by the following parameter values (typical of a smart-metering service):

- 8.500 Aggregation Nodes;
- Transmission Interval: 30 minutes;
- Ratio of authentication that needs to get parameters from HLR ($R_{auth_{HLR}}$): 20%;
- Average Packet size (P_{size}): 130 bytes;
- Gr uplink capacity (w_{Gr}): 1 Mbps;
- Other interfaces uplink capacity: 10Mbps.

The parameters that were considered in this sensitivity analysis were the transmission interval, the ratio of authentication that needs to get parameters from HLR, the average Packet size and the number of SMSs per hour.

The results of this analysis are presented on Figure 7, from where it can be observed that the transmission interval will be the most influential constraint for the considered M2M services. For small values of transmission interval, the impact of M2M overheads can vary noticeably, particularly in Gr and Iu-PS. Concerning the other parameters at study, no major design constraints are expected, except for services that will require a considerably large amount of SMSs.

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VIII. Conclusion and Future Work

This paper presented mathematical models that can be useful to better understand the effects of M2M related traffic into cellular telecommunications networks. As a result of this work a prototype for a computational tool was developed, that is believed to be of value to MNOs and future research in this field. The results presented, although mainly illustrative, support the usefulness of this models and tool. The presented work needs further developments and improvements, mainly in the orchestration of usage scenarios, which implies an extended development of the proposed models and a deeper knowledge on the characteristics of M2M traffic sources, accordingly to different types of services and usage scenarios. Although influenciated by previous work [8][9], the models presented on Section III represent a novel insight to study the UMTS Packet Core. Their application to the study of M2M communications is, to the best knowledge of the authors, a new application to such model. The resultant computational tool has already proven to be of practical benefit to real world application.

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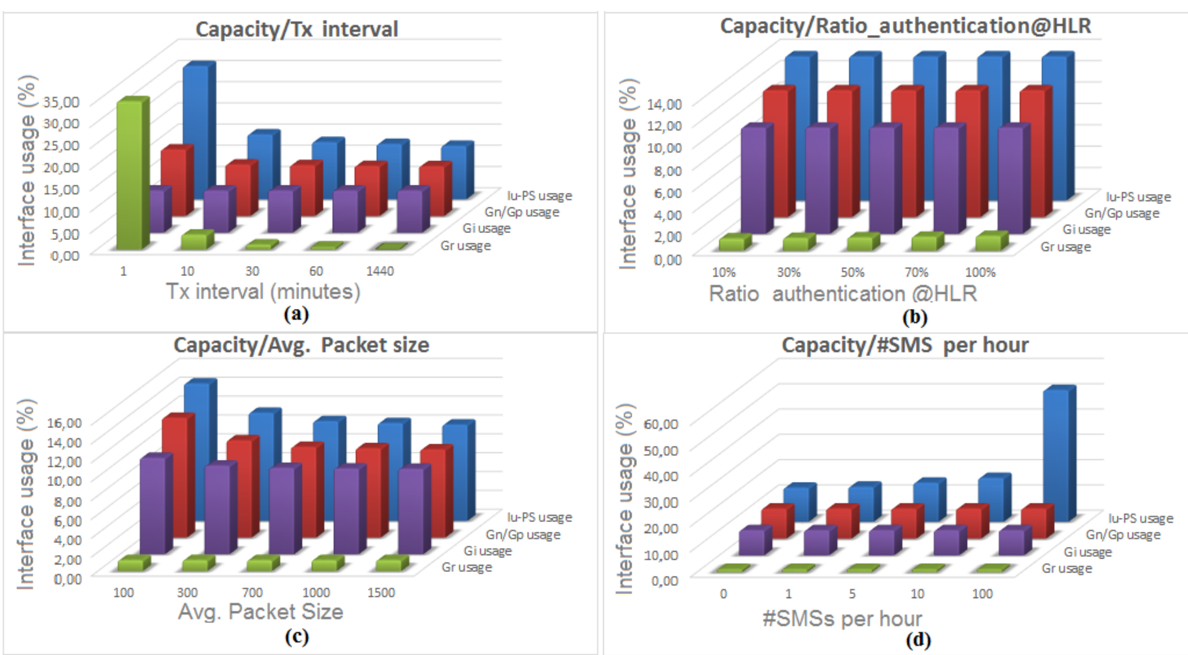

Figure 7. Sensibility analysis results: (a) Varying .the transmission interval; (b) Varying the ratio of authentication that needs to obtain parameters from the HLR; (c) Varying the average Packet size; (d) Varying the number of SMSs per hour