Technical vulnerability of the E-UTRAN paging mechanism

Alexey Baraev*†, Urtzi Ayesta°‡, Ina Maria (Maaike) Verloop◇‡, Daniele Miorandi* and Imrich Chlamtac*
* CREATE-NET, v. alla Cascata 56/D, 38123 – Povo, Trento (Italy)
name.surname@create-net.org
† DISI, University of Trento, v. Sommarive 5, 38123 – Povo, Trento (Italy)
° CNRS ; LAAS ; 7 avenue du colonel Roche, 31077 Toulouse, France
urtzi@laas.fr
‡ Université de Toulouse, LAAS, INP, Toulouse, France
◇ CNRS-IRIT, 2 rue C. Camichel, 31071 Toulouse, France
maaike.verloop@enseeiht.fr

***Abstract*—The signalling subsystem is the most expensive and complex element in cellular networks. Today's networks use signalling mechanisms whose design builds on more than 20 years of the operational expertise. Despite this, the signalling subsystem of all mobile network standards remains vulnerable to failures of equipment and to sharp increases in offered load caused by unanticipated traffic patterns. In this work we analyse the technical vulnerability of paging - a key signalling mechanism that is responsible for notifying mobile terminals of downlink service requests. Our assessment considers the operation of Long-Term Evolution (LTE) networks and in particular the performance of the paging mechanism on the radio interface. We implemented the paging procedure in a simulator, and we propose and verify a mathematical model of the system behaviour. The proposed mathematical model effectively captures the non-zero threshold of paging failure probability; it is scrupulously precise for the paging loads below the non-zero threshold and delivers a close approximation with the increasing paging load. The mathematical model can be applied to optimise the performance of the paging mechanism and to devise techniques able to overcome its technical vulnerability.**

I. Introduction

Outage events and unanticipated changes in user behaviour represent one of the major difficulties in the operation of cellular networks and, at the same time, a major opportunity for improvements. It is the signalling subsystem that defines the stability of the network operation in such conditions. Although the majority of the signalling mechanisms have already been used for almost two decades, some of them fail in the situations of force majeure and cannot provide a stable network operation. This publication makes a particular emphasis on the paging procedure and offers an analysis of the MME (Mobility Management Entity) paging mechanism that is used in LTE (Long-Term Evolution) networks.

Mobile networks use the paging mechanism in the connection establishment procedure for the mobile–terminated service requests for both circuit– and packet–switched (i.e., data) services. Paging helps to find a requested user terminal in the network and initiate a connection establishment procedure. The management of the paging procedure is a responsibility of a core network entity in most cellular network standards, and notably in the 3GPP (the 3rd Generation Partnership Project): MSC (Mobile Switching Centre) for circuit–switched services and SGSN (Serving GPRS Support Node) or MME for packet–switched services. The standards define the physical, transport and logical channels in the downlink on the radio interface that are used to deliver paging requests to user terminals (UE). The uplink channels that carry paging response messages are also defined by the standards. Moreover, the standards define the formats of the paging request and paging response messages as well as the procedures that must be executed by UEs, base stations and the mobility management entities (MSC, SGSN, MME) when handling the paging.

Having the paging procedure specified in the standards, the network operators have flexibility in configuring the required paging capacity on the radio interface. In addition, the operators can specify the type of the mobile identity to be used in paging messages, the maximum number of paging repetitions and the timeouts associated with the paging requests. Currently, operators make conservative choices on the setting of such parameters, using rule of thumbs based on their experience with the operations of production networks deployments. Indeed, the literature misses a coherent and holistic framework for assessing the impact of such parameters on the system–level performance and for providing guidelines on their configuration.

In LTE three paging mechanisms are defined: MSC paging, SGSN paging and MME paging. In this work, we focus on MME paging, which is the paging that is used for EPS (Evolved Packet System) services in E-UTRAN (Evolved Universal Terrestrial Radio Access Network). The main contributions of our work can be summarized as:

- We provide an in–depth analysis of the technical vulnerability of the E-UTRAN paging mechanism in the presence of network outages;
- We develop a mathematical model, based on retrial queuing systems, for assessing the blocking probability of paging request messages and the probability of paging failures;
- We validate the proposed model by comparing it with the outcomes of computer-aided simulations, based on a detailed implementation of the MME paging functioning.

The remainder of this paper is organized as follows. In Sec. II we describe the MME paging mechanism in E-UTRAN. In Sec. III we describe the issues that may arise with MME paging in the presence of network outages. Sec. IV presents a mathematical model of the system behaviour.

Simulation results are presented in Sec. V. Sec. VI describes related work and the state-of-the-art in the field. Sec. VII concludes the paper pointing out directions for future research.

II. MME PAGING FOR EPS SERVICES

The MME paging for EPS (Evolved Packet System) services [1], [2], [3] is a part of the connection establishment procedure for the downlink data service requests. It is used in the evolved LTE systems in parallel with the MSC and SGSN paging mechanisms that are applied for service requests of other types. The RRC (Radio Resource Control) paging request messages that are used in the MME paging can carry S-TMSI (S-Temporary Mobile Subscriber Identity) or IMSI (International Mobile Subscriber Identity) of the paged mobile terminals. S-TMSI is a 40-bit long identifier that is unique in a given tracking area (TA) list, i.e. in a network segment with a number of cells. IMSI is 64 bits long; it uniquely identifies a SIM card on the global scale and thus in a particular mobile network.

The MME is the network entity responsible for paging for EPS services. Its task in the paging context is to initiate the paging procedure and manage it entirely. Thus, MME generates S1-AP paging messages upon reception of the downlink data notification messages from SGW (Serving Gateway) [4]. It sends an S1-AP paging message to all base stations in the TA list that the MME provided to the paged UE during the most recent TA update. At the moment when an S1-AP is sent the MME starts the T3413 timer for the paged UE. The T3413 limits the period in which the MME considers the issued S1-AP valid and expects a response to it from the paged UE.

All base stations that belong to the paged TA list receive the S1-AP paging request, decode the UE identity from it and place a corresponding paging request into the paging buffer where it has to wait for the next paging occasion. With the first available paging occasion the base station has to include the UE identity into the RRC paging message [5] that it transmits to the UEs in its coverage area. However, the size of the RRC paging message is limited, and therefore, it is possible that the base station cannot send the paging request in the first PO (Paging Occasion). In such case it makes further attempts to transmit the paging request with the subsequent paging occasions. The eNb (base station) equipment can have configurable settings that limit the maximum number of attempts to transmit a paging request or, alternatively, such settings can limit the period in which eNb attempts to transmit a paging request. This depends on the design of particular eNb equipment and varies between vendors.

User terminals in the idle mode have to monitor the paging occasions and decode the UE identities transmitted in POs [2]. An UE returns to the idle mode if does not recognise its identity in the list of identities decoded from a PO. When an UE recognises its identity it has to respond to the paging by transmitting a service request message, as it is defined in [6], [4]. However, an UE has to ignore any paging request in case it undergoes any EMM (EPS Mobility Management) procedure or service request procedure at the moment it receives a paging request [2].

The service request messages that UEs send in response to the paging are forwarded to the MME. When the MME receives such message, it stops the T3413 timer and proceeds with the connection establishment procedure.

If the MME does not receive a response to a paging request within the period of time defined by the T3413 timer, it may repeat the paging and restart the T3413. The maximum number of paging repetitions is a configurable parameter of the MME equipment. Operators normally limit it to one repeated paging request. The type of UE identity that is normally used in the repeated paging is IMSI, while S-TMSI is used for primary paging, as it saves the resources on the radio interface.

III. ISSUES IN THE PRESENCE OF NETWORK OUTAGES

Reliable paging is important for a stable operation of mobile networks. The efficiency of the paging depends mainly on the operation of the signalling channels that are used to transport the paging messages. A possible difficulty in the operation of the paging procedure is the overload of the paging channels on the radio interface. Most often it occurs as a result of an outage or unusual user behaviour. In terms of the traffic capacity, such events affect several sites from a tracking area – the sites which take the excess load. However, as the paging is performed on a basis of tracking areas, such events affect these entire areas with 15 – 30 sites. Thus they cause service disruptions also on sites which are not affected by the events directly, i.e. which have fully operational traffic channels, but which are within the same tracking/location area. To illustrate such service disruption we refer the reader to Fig. 1, which shows a situation in an LTE cell that is affected by an outage of one or more neighbour cells.

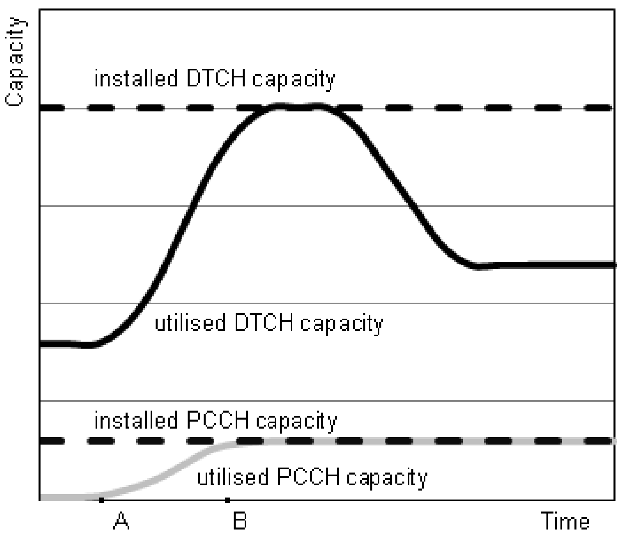

Fig. 1: Overload of signalling channels: the installed traffic capacity is not utilized effectively

Due to an outage of several sites in a tracking area (point A on Fig. 1) a share of users are dropped from the network. Some of the users previously served by the failed cells register in other cells while a significant number of users remain out of coverage. The disconnected users are still registered in the tracking area. Therefore, the MME continues to page them when it receives notifications from the SGW. The demand for the PCCH (Paging Control Channel) capacity surges as the MME does not receive paging response messages and has to repeat paging. The secondary paging is performed with the IMSI in the paging requests. It requires higher PCCH capacity than in the case of the primary paging which uses S-TMSI. Field statistics shows that it takes as little time as several minutes before the PCCH load reaches the installed PCCH capacity (point B on the figure). After another 7-9 minutes depending on the design of the equipment, the DTCH (Dedicated Traffic Channel) carried traffic starts to decline as the overall time of transmission of paging requests now exceeds the timeout setting in the MME. Hence the cells in the affected tracking area enter such state in which they report a high blocking rate while having DTCH capacity available. However, the available DTCH capacity cannot be utilized due to overload of the PCCHs.

If a network operates according to the current specifications, the described situation of PCCH overload would require an intervention from engineers, or otherwise it could not be resolved. Thus, it is an opportunity for a research with a clear target which can lead to a release of a commercial solution. Equipment manufactures and network operators have already raised this issue, nevertheless it is neither addressed in the specifications nor in the equipment. The Related Work section provides the reader with the details on the relevant activities within 3GPP and describes some measures that vendors undertake to improve the performance of their equipment.

IV. A Model for MME Paging

We model the system at hand as a retrial queue [7] [8] [9]. A retrial queueing system consists of a service facility and an orbit, as sketched in Fig. 2. Customers arriving from outside the system and finding the service facility full may join the orbit and conduct a retrial later. Same applies to customers arriving from the orbit. When the service facility is not full, customers arriving enter it to get served.

With reference to the MME paging as described in Sec. II, customers correspond here to paging requests. The service facility corresponds to the ensemble of eNb paging buffer and PCCH channel. When the eNb paging buffer is full, the request does not get served (i.e., it enters the orbit in the retrial queue jargon), and, upon expiration of the T3413 timer, another request is sent. As the eNb cannot send more than one RRC paging message at a time, the service facility consists of a single–server queue.

In modelling the system, we make a number of simplifying assumptions. In the following section we will evaluate numerically the impact of such assumptions on the predicted system–level behaviour.

Requests are assumed to arrive according to a Poisson process of intensity λ. Each request requires a serving time, which is assumed to be exponentially distributed with mean $1/\mu$[1]. The queue has a finite buffer space able to accept K requests. An incoming request that finds the buffer full is sent to the orbit. We denote by q the (unknown) probability that the buffer is full, in steady state. At the orbit, requests are associated to a timer, again modelled as an exponential distribution with mean $1/\theta$[2] Once the timer expires a retrial is generated. Retrials are performed only once for each request, according to the customary operations in E-UTRAN (see Sec. II). The service time of a retrial is approximately $\frac{8}{5\mu}$[3]. Given the complexity of the model, analytical expressions for the performance seem out of reach. Therefore we resort to approximate analysis in order to get a closed-form expression for q. In order to capture the two different service rates, we define an effective "average" service rate. In order to do so we note that the effective arrival rate to the server from outside is $\lambda(1-q)$ and that the effective arrival rate to server from the orbit is $\lambda q(1-q)$. Thus, the probability that an incoming job comes from outside (orbit) is $\frac{1}{1+q}$ ($\frac{q}{1+q}$), respectively. We therefore define an "average" mean service rate as:

$$\tilde{\mu} = \frac{1}{1+q}\mu + \frac{q}{1+q}5\mu/8 = \frac{\mu(1+5q/8)}{1+q}.$$

We consider the joint process $(C(t), N(t))$, where $C(t)$ is the number of customers in the service facility at time t and $N(t)$ is the number of customers in the orbit at time t. We denote by K the buffer size of the service facility. The transition rates of the process $(C(t), N(t))$ are given by:

$$(c,n) = \begin{cases} (c,n+1) & \text{with rate } \lambda & \text{if } c=K \\ (c,n-1) & \text{with rate } n\theta & \text{if } c=K \\ (c-1,n) & \text{with rate } \tilde{\mu} & \text{if } c>0 \\ (c+1,n) & \text{with rate } \lambda & \text{if } c<K \\ (c+1,n-1) & \text{with rate } n\theta & \text{if } c<K \end{cases} \quad (1)$$

We note that the departure rate $\tilde{\mu}$ in (1) is in fact an approximation. Given the blocking probability q, and assuming that the events $\{\text{customer } i \text{ finds the facility full}\}_i$ are independent and identically distributed, the orbit system can be modeled as an $M/M/\infty$ queue with arrival rate λq and service rate θ. This implies that the number of users in the orbit is a Poisson distribution with mean $n^* = \lambda q/\theta$. We consider the 1-dimensional process $\tilde{C}(t)$ with arrival rate $\lambda + n^*\theta = \lambda(1+q)$ if $\tilde{C}(t) < K$ and arrival rate 0 otherwise, and departure rate $\tilde{\mu}$, that is, $\tilde{C}(t)$ is an $M/M/1/K$ queue. For this system the steady-state distribution of the number of

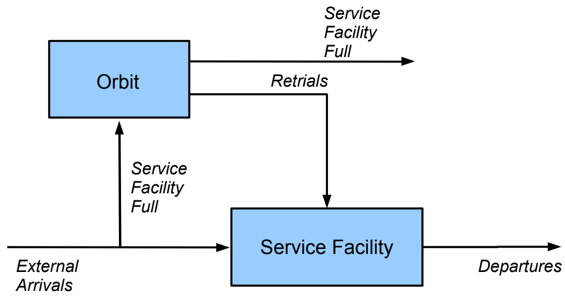

Fig. 2: Retrial Queue Model (from [7]).

[1]In the real system the service time is deterministic, as it is the time necessary to send the message through the PCCH. In the next section we will assess the impact of such an assumption.

[2]Also in this case, we are approximating a deterministic value (the T3413 timer) with an exponential distribution. Next section will show the impact of such an approximation.

[3]This reflects the fact that in the retrial IMSI identifiers (64 bits long) are used instead of S-TMSI ones (40 bits long), which are used for the first attempt. In reality the functioning is more complex, as it depends on the capacity of each paging occasion, which in turn depends on a number of parameters that can be set by the operator, see the discussion in the next section. In the model we decided to keep $64/40 = 8/5$ as the ratio between the service time of a retrial and that of an externally arriving customer.

customers in $\tilde{C}(t)$ is given by:

$$\tilde{\pi}(k) = \frac{(1-\lambda(1+q)/\tilde{\mu})(\lambda(1+q)/\tilde{\mu})^k}{1-(\lambda(1+q)/\tilde{\mu})^{K+1}}, k = 1, \ldots, K. \quad (2)$$

Approximating the process $C(\cdot)$ by $\tilde{C}(\cdot)$, the blocking probability q is the solution of the fixed-point equation $q = \pi(K)$, i.e.,

$$q = \frac{(1-\lambda(1+q)/\tilde{\mu})(\lambda(1+q)/\tilde{\mu})^K}{1-(\lambda(1+q)/\tilde{\mu})^{K+1}}. \quad (3)$$

We have the following characterization of the solution of (3).

Proposition 1. *The fixed point (3) has a unique solution. The solution can be found by the fixed point iterations*

$$q^{(n+1)} = \frac{(1-\lambda(1+q^{(n)})/\tilde{\mu})(\lambda(1+q^{(n)})/\tilde{\mu})^K}{1-(\lambda(1+q^{(n)})/\tilde{\mu})^{K+1}}, \quad (4)$$

which converge for any initial $q^0 \in [0, 1)$.

Assuming that the probability of discard is the same for the original requests and for the ones coming from the orbit, and that these two events are independent, we can approximate the probability that a customer is unsuccessful in both primary and secondary requests as:

$$p_{fail} \approx q^2. \quad (5)$$

In the next section we will validate our model by comparing (5) with the outcomes of numerical simulations obtained by implementing the actual functioning of the MME paging mechanisms.

V. Performance Evaluation

A. Simulator Description

We developed a Matlab simulator of the MME paging mechanism. The software that we developed for the paging experiments models the following operations performed by the MME:

- Processing of the downlink data notification messages;
- Generation and transmission of primary and repeated S1-AP paging messages;
- Monitoring of the T3413 timer.

The modelled operations that are performed by the eNb are the following:

- Scheduling of paging frames and paging occasions in accordance with the configuration of the cells;
- Buffering of the received S1-AP paging messages;
- Generation and transmission of the RRC paging messages;
- Monitoring of the paging discard timer.

The experiment focuses on the operation of (i) the radio interface and (ii) the base stations, and hence the software includes mechanisms to log the various events taking place within such entities, providing the means for monitoring their performance.

Simulator Configuration: The model implements the frame structure type 1 with 5 MHz bandwidth allocated to the cells. The system parameters that are used in the model are listed in the Tab. I.

Parameter	*Value*
System bandwidth	5 MHz
Frame structure	Type 1
Number of frames in the DRX cycle	128
Number of paging occasions per radio frame	1/16
Maximum number of S-TMSI paging records in the RRC paging request	7
Timer T3413	5.0 sec
Maximum number of retransmission attempts	1
Primary paging type	S-TMSI
Secondary paging type	IMSI
Size of the paging buffer at eNb (in paging records S-TMSI or IMSI)	160

TABLE I: Simulation settings.

Paging capacity on the radio interface: The model calculates the paging capacity of the cells using the parameters from Tab. I. All these parameters are configurable and can be modified for particular experiments. The paging capacity of a cell is defined as per the following algorithm.

1) Duration of the DRX cycle (discontinuous reception cycle) is defined by the number of frames in it. The frame is 10 ms, so the DRX cycle of 128 frames has a duration of 1280 ms.
2) Number of paging occasions in a DRX cycle is defined by the number of paging occasions configured in a single frame ($1/16$ in the experiment). Thus, a DRX cycle with 128 frames provides 8 paging occasions.
3) Each of the 8 paging occasions provides capacity for a maximum of 7 S-TMSI paging records (one RRC paging request). Thus, 56 user terminals can be paged with S-TMSI in a single DRX cycle of 1280 ms.
4) Changing the base from the DRX cycle to per-second value gives 43.75 S-TMSI pages per second.

Traffic characterisation: The arrival of the downlink data notification messages from SGW is modelled as a Poisson arrival process with average inter-arrival time given by the BHCA (Busy Hour Call Attempts - number of connection establishment attempts in the busiest hour of a day). Thus, the average inter-arrival periods considered in the presented experiments range from 12 to 72 ms, what corresponds to the BHCA values of $300,000$ to $50,000$ respectively. Unreachable user terminals, i.e. the UEs that went out of coverage without communicating this event to the network, typically represent 3% to 5% of the total number of users registered in a tracking area. In real networks this percentage depends on the quality of the network planning and operation. The experiments use a value of 0% as a normal percentage of unreachable users. This is due to the fact that our mathematical model does not consider unreachable users at the current phase of the project. The simulations include paging with target BHCA values in a tracking area. All cells in the TA have an identical configuration that provides paging capacity of 43.75 S-TMSI per second as described earlier. Paging response messages (service requests in the uplink) and the corresponding control channels are not modelled in the simulator; we consider the operation and the status of the paging buffer instead.

B. Evaluation

Probability of failure of a connection establishment attempt (Failure Probability): The probability of failure of a connec-

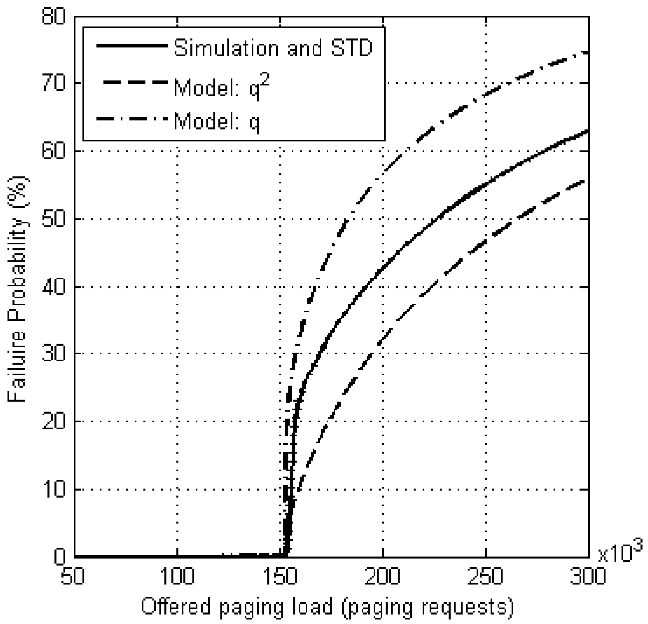

Fig. 3: Probability of failure of a connection establishment attempt

tion establishment attempt (Failure Probability) is defined as a ratio of the total number of unsuccessful connection establishment attempts to the total number of connection establishment attempts. A successful connection establishment attempt is logged when either primary or secondary paging request to a particular user is successful. An unsuccessful connection establishment attempt is logged when both the primary and the secondary paging requests to a particular user fail. In terms of the mathematical model described in Sec. IV the probability of failure of a connection establishment attempt corresponds

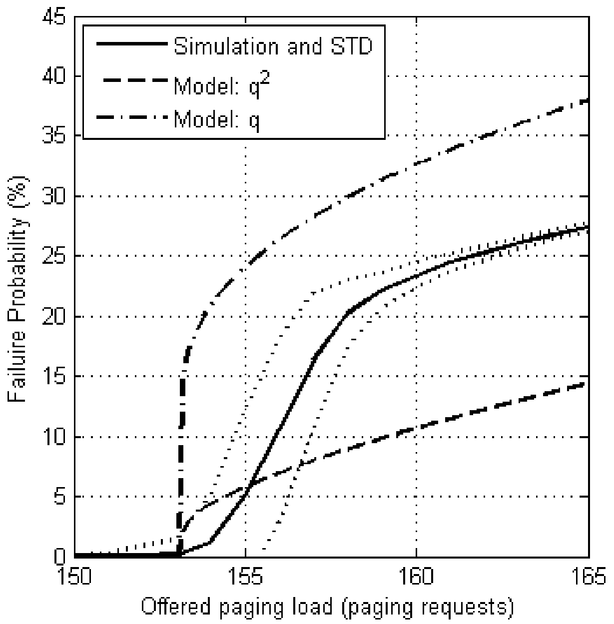

Fig. 4: The non-zero threshold on the graph of Probability of failure of a connection establishment attempt

to q^2 assuming that the probability of discard of a request is the same for the original requests and for the ones coming from the orbit.

In our assessment of the probability of paging failure we use the system configuration given in the Tab. I. Each run simulates 1800 seconds of network operation. Fig. 3 shows the resulting curve for the probability of paging failure, which is based on average values from 500 runs. In Fig. 3 we report the results of the simulations as well as computations in which we use the mathematical model presented in Sec. IV. The probability of paging failure in the simulations is defined as the probability of primary paging failure (S-TMSI) multiplied by the probability of secondary paging failure (IMSI). The probability of paging failure in the approximation is defined by the equation (5) where q is computed using the equation (3).

The results reported in Fig. 3 show that the proposed mathematical model effectively captures the non-zero threshold of paging failure probability. Moreover, it is scrupulously precise for the paging loads below the non-zero threshold. We consider the q and q^2 as the upper and the lower bounds of the Failure Probability. As described in Sec. IV, q^2 refers a process where the probabilities of failure of a primary and a secondary paging requests are completely independent. q represents the probability of failure of a connection establishment attempt in a process where the probabilities of failure of a primary and a secondary paging requests are completely correlated. In the simulations, the probability of paging failure starts rising from zero with the BHCA load of 151000 attempts where it is a low as 0.0058%, and it reaches 0.14% with the BHCA of 153000 attempts (Fig. 4). The mathematical approximation captures the non-zero probability threshold at 153200 BHCA (2.11%), thus approaching the experimental threshold closely.

The non-zero probability threshold is the most important point on the loads axis, as it separates two operational modes of the paging channel. Cellular networks operate the paging channels in the region with a zero probability of paging failure. Thus, having captured this threshold with the mathematical model we can proceed with the development of solutions for improvement of the technical vulnerability of the paging mechanism in E-UTRAN.

VI. Related work

The paging mechanism is one of many functionalities of the signalling subsystem of any mobile network [10]. When a new standard, such as LTE, is developed, the signalling system proposed for it undergoes continuous modification before it is accepted. This process is driven by technical groups inside the 3GPP, which bring together representatives of major equipment vendors and service providers. Once the specifications are approved and accepted, the equipment vendors can still introduce modifications into the signalling subsystem of their infrastructure equipment, maintaining however the operational principles that they agreed in the specifications. Thus, the freedom for making changes after the specifications have been accepted is significantly limited as mobile network uses equipment from several suppliers, and the network entities have to be able to mutually interoperate.

Reports by 3GPP technical groups contain a number of proposals to improve the paging mechanism in E-UTRAN. In the context of vulnerability, the most relevant proposals are [11], [12] by Motorola, which suggest sending the primary paging request only to the cell where the paged user terminal was last observed instead of paging the whole TA list. The proposals deal with the paging delay that such approach would cause but at the same time the authors claim that the paging load can be reduced by 50% to 90%. Such decrease in the paging load would undoubtedly lower the risks of PCCH overload and improve the technical vulnerability of the paging mechanism. However, the recent Release 10 specification [3] does not include the modification that the authors proposed, what suggests that the proposal was not accepted by the group. Nevertheless, the authors registered their idea in the prior art database where it is available for download [13].

In late 2009 China Mobile, a company that operates the world's busiest network, brought a similar item to the 3GPP agenda. The company proposed an optimisation to the paging mechanism [14] where the MME would again use the last known cell information, but in addition it would also page the neighbours of the last known cell directly via S1 (MME to eNb) or indirectly via X2 (eNb to eNb) interfaces. Thus, according to this scheme the primary paging request is sent to a limited number of cells, and the secondary paging is performed on the entire TA list. The current Release 10 specifications do not include this paging scheme; therefore, the question of paging load reduction is still open.

As the paging mechanism has remained unchanged throughout all releases of the 3GPP LTE specifications, we do not expect any change in the upcoming Release 11 or the later releases, if any. In fact, the large manufacturers of the infrastructure equipment have an alternative way to implement their desired modifications to the signalling subsystem that they extensively used in GSM and UMTS. They can implement their solutions in their equipment, and if the impact of such solution is limited by the network entities supplied by a single vendor, there are no interoperability conflicts in the network. An example of such solution is the paging discard timer that is not defined in the 3GPP specifications. The timer allows the base stations to remove expired paging messages from operation. Realised by some vendors, it is their proprietary solution that resides in the eNb and effectively improves the technical vulnerability of the paging mechanism without any negative impact on the network entities supplied by other vendors, if they are present in the network. However, the details on such proprietary solutions are only available to the vendors and their customers, and therefore we cannot evaluate their effectiveness.

VII. Conclusions

In this work we have analysed the technical vulnerability of the E-UTRAN paging mechanism in LTE cellular networks. In the presence of network outages or abnormal user behaviour, indeed, the network may reach a state in which the available traffic capacity (on DTCH channels) is not fully utilized, due to the overload of the PCCH channels and hence the impossibility of establishing connections with user equipment. This vulnerability is rooted in the way the paging mechanism is engineered in E-UTRAN.

In this work, we have presented a stochastic model (based on retrial queueing systems theory) for the operations of the MME paging mechanism in E-UTRAN. The model was shown, by comparison with the outcomes of computer-aided simulations, to be able to predict rather well the paging failure probability under various load conditions. From an operational perspective, one parameter of relevance is the load at which the paging failure becomes non-null. Simulations showed that our model is able to predict such a figure with a good level of accuracy.

Directions for future research include (i) an extension of the model in order to study the paging buffer occupancy statistics (ii) the introduction of appropriate control mechanisms (e.g., active queue management techniques, dynamic allocation of channel resources) for optimizing the performance of the paging mechanisms in LTE networks.

References

[1] 3GPP, "Universal mobile telecommunications system (UMTS); LTE; non-access-stratum (NAS) protocol for evolved packet system (EPS); stage 3," Specification Specification 3GPP TS 24.301 version 10.3.0 Release 10. [Online]. Available: http://www.3gpp.org

[2] ——, "LTE; evolved universal terrestrial radio access (E-UTRA); user equipment (UE) procedures in idle mode," Specification 3GPP TS 36.304 version 10.2.0 Release 10. [Online]. Available: http://www.3gpp.org

[3] ——, "LTE; evolved universal terrestrial radio access (E-UTRA) and evolved universal terrestrial radio access network (E-UTRAN); overall description; stage 2," Specification 3GPP TS 36.300 version 10.4.0 Release 10. [Online]. Available: http://www.3gpp.org

[4] ——, "LTE; evolved universal terrestrial radio access network (E-UTRAN); S1 application protocol (S1AP)," Specification 3GPP TS 36.413 version 10.2.0 Release 10. [Online]. Available: http://www.3gpp.org

[5] ——, "LTE; evolved universal terrestrial radio access (E-UTRA); radio resource control (RRC); protocol specification," Specification 3GPP TS 36.331 version 10.2.0 Release 10. [Online]. Available: http://www.3gpp.org

[6] ——, "LTE; general packet radio service (GPRS) enhancements for evolved universal terrestrial radio access network (EUTRAN) access," Specification 3GPP TS 23.401 version 10.4.0 Release 10. [Online]. Available: http://www.3gpp.org

[7] V. G. Kulkarni and H. M. Liang, "Retrial queues revisited," in *Frontiers in queueing*. Boca Raton, FL, USA: CRC Press, Inc., 1997, pp. 19–34.

[8] J. R. Artalejo and A. Gómez-Corral, *Retrial Queueing Systems: A Computational Approach*. Springer, 2008.

[9] G. I. Falin and J. G. C. Templeton, *Retrial Queues*. CRC Press, 1997.

[10] Y.-B. Lin and I. Chlamtac, *Wireless and Mobile Network Architectures*. John Wiley and Sons, 2001.

[11] 3GPP, "Paging load reduction in synchronized cells," Technical document 3GPP R3-070965 of TSG-RAN-WG3 Meeting 56. [Online]. Available: http://www.3gpp.org

[12] ——, "Paging load reduction in asynchronous cells," Technical document 3GPP R3-081412 of TSG-RAN-WG3 Meeting 60. [Online]. Available: http://www.3gpp.org

[13] M. B. L. Lopes, J. Harris, "Scheme for paging optimization," Technical disclosure IPCOM000 192 990D, 2010, by Motorola Inc. [Online]. Available: http://ip.com/IPCOM/000192990

[14] 3GPP, "Solutions for paging optimization," Technical document 3GPP R3-092204 of TSG-RAN-WG3 Meeting 66-bis. [Online]. Available: http://www.3gpp.org