A Self-Organized Tracking Area List Mechanism for Large-Scale Networks of Femtocells

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Abstract — **In this paper we explore the concept of self-organized location management in large-scale networks of femtocells (NoFs). A NoF is a mesh network that provides multi-hop connectivity amongst femtocells and, in turn, to the Evolved Packet Core. One of the most challenging issues in NoFs is location management, i.e., the process of determining the location of a User Equipment (UE) in the network. Standard 3GPP location management mechanisms are not well suited for large-scale NoFs due to the overhead generated by frequent handovers and cell reselections. In this paper we propose a self-organized Tracking Area List (TAL) mechanism that seamlessly monitors the mobility state of each UE in order to adjust the size of its individual TAL dynamically. Analytical results show that our mechanism reduces location signalling traffic in the cellular network compared to standard 3GPP schemes. In addition, the self-organized TAL mechanism is fully compliant with 3GPP LTE Technical Specifications, which facilitates its implementation in a commercial scenario.**

Keywords: Long-Term Evolution; Network of Femtocells; Self-Organized Tracking Area Lists; Mobility management; Location management

I. INTRODUCTION

Standalone LTE femtocells (also referred to as Home eNBs) are receiving much attention from the industry and the academia as a cost-effective solution to provide LTE coverage in indoor scenarios. Opposite to this approach, a novel deployment concept, referred to as large-scale network of femtocells (NoF), is being studied in the context of the European project BeFEMTO [1]. In a NoF, femtocells collaborate with each other in order to optimize the operation of the cellular network. One of the most challenging issues of large-scale NoFs is location management, i.e., the process of managing databases that store the location of User Equipments (UEs) within the network of femtocells.

Standard 3GPP location management mechanisms have been designed with macrocell scenarios in mind. Therefore, their performance in large-scale networks of femtocells is far from optimal due to the overhead generated by frequent handovers and cell reselections. Thus, NoF scenarios require specific location management mechanisms in order to track UEs efficiently whilst keeping location signalling traffic under control.

In this paper we propose a self-organized Tracking Area List (TAL) mechanism to reduce location management traffic in large-scale networks of femtocells. Self-Organizing Network (SON) use cases have been recently discussed in 3GPP [2]. However, when dealing with mobility management, the focus is mainly on handoff management instead of on exploiting the benefits of Tracking Area Lists. TALs are a feature first introduced in 3GPP Release 8 that allows the Evolved Packet Core to register UEs to more than one Tracking Area (TA) simultaneously [3]. Our proposal uses this feature to reduce location signalling traffic in large-scale networks of femtocells. This is achieved by registering UEs to individual TALs that are able to adjust their size in a self-organized fashion, i.e., without common centralized network planning. Analytical results show that the self-organized TAL mechanism can generate up to a 39% less location signalling traffic per UE than the conventional TAL mechanism.

The remainder of this paper is organized as follows. Section II provides a background on location management in LTE networks. This is followed by a discussion on previous research work in Section III. A description of the self-organized Tracking Area List mechanism and its analytical model is provided in Section IV. Section V discusses the performance evaluation of the proposed scheme. Finally, Section VI concludes the paper.

II. LOCATION MANAGEMENT IN LTE NETWORKS

In 3GPP systems, a UE can be in two basic operational modes: *idle* and *connected* [4]. In idle mode, a UE does not have a dedicated connection with the network, although it can receive system information by listening to broadcast channels. In connected mode, a UE has a dedicated connection with the network as a result of an ongoing voice or data transmission.

In idle mode, the location of a UE within the LTE network is known on a Tracking Area granularity. A TA is a group of cells that are tracked by a Mobility Management Entity (MME) in the network. In order to keep its location updated in the MME, a UE needs to perform a Tracking Area Update (TAU) procedure every time it enters a new TA. When the network needs to forward an incoming voice call or data packet to a UE in idle mode, the MME locates the UE by sending paging messages to all cells in the UE's last registered TA. Upon receipt of a paging message, the UE establishes a connection with the network, thus moving from idle to connected state.

As of Release 8 of 3GPP Technical Specifications [3], the location of a UE within the LTE network is known on a

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Tracking Area List granularity, i.e., a group of Tracking Areas. Therefore, a UE needs to perform a TAU procedure every time it enters a TA that is not included in its TAL. Tracking Area Lists reduce location signalling traffic and extend battery life by preventing UEs from performing a TAU procedure when hopping between two cells located in different TAs.

III. RELATED WORK

Previous research work has been carried out in the area of adaptive location management in cellular networks [5], [6], [7], [8], [9], [10], [11]. However, most of these proposals address the problem from a theoretical perspective and, in general, do not consider the collateral effects of their implementation (e.g., high volumes of spurious location signalling traffic throughout the network). Furthermore, some of these schemes do not comply with 3GPP LTE Technical Specifications, which further compromises their implementation in a commercial scenario, as explained below.

In [9] and [10], the authors propose a mechanism to reduce location signalling traffic in LTE networks using Tracking Area Lists. Both schemes deliver an optimized TAL configuration to all UEs in the network based on signalling calculations made by individual cells. While technically sound, these proposals have some important caveats. First, the system cannot guarantee a global minimum for location signalling traffic, as each cell makes autonomous decisions without considering the impact of global TAL reconfigurations on neighbouring cells. Secondly, delivering periodical TAL reconfigurations to all UEs in the network generates a significant amount of spurious location signalling traffic, as a large number of UEs will be forced to perform a Tracking Area Update procedure in order to adapt to the new TAL configuration. Therefore, the adequacy of these mechanisms in commercial scenarios is called into question.

In [11], the authors propose a mobility/traffic adaptive location management mechanism that registers UEs to dynamic TAs in order to reduce location signalling traffic in the cellular network. This mechanism derives the optimal number of cells in the forthcoming TA from live speed and call arrival rate measurements. Thus, UEs are required to send these parameters to the network every time they enter a new TA.

Both the network and the UEs can estimate the call arrival rate by averaging the number of incoming calls during a period of time. However, providing the network with accurate UE speed measurements is not straightforward. To solve this, the authors propose two methods:

- UEs measure their speed using a GPS receiver.
- UEs estimate their speed by combining internal time measurements with geographical coordinates advertised by the old and new base stations.

The first method is not realistic for several reasons. First, not all commercial UEs are equipped with embedded GPS receivers. Second, GPS signals might not always available, particularly in indoor and dense urban scenarios. And third, UEs are put into idle mode to reduce power consumption. This is not consistent with keeping a GPS receiver tracking and processing satellite signals on a regular basis.

The second method is difficult to implement in a network of femtocells, as HeNBs might not always be able to advertise their geographic coordinates (e.g., indoor deployments, non GPS-enabled femtocells, etc.). Furthermore, the mechanism described in [11] is based on network-wide Tracking Area reconfigurations, which have a significant impact on spurious location signalling traffic.

IV. MECHANISM DESCRIPTION

In this section we propose a 3GPP-compliant self-organized Tracking Area List mechanism for large-scale networks of femtocells. Our scheme can be deployed in legacy MMEs by means of a software update and does not require modifications to the UE.

Prior to the description of the self-organized mechanism, we need to characterize the mobility pattern of a UE in order to estimate the average TAU arrival rate in a TA ($\bar{\lambda}_{TAU}$). This is done in subsection IV.A. A detailed description of the self-organized TAL mechanism, along with an analytical model for its performance evaluation, is provided in subsection IV.B.

A. Mobility Model

In [12], the author provides a comprehensive overview on mobility models for cellular networks. In this paper we have assumed a Markov-based mobility model for a 2D hexagonal topology in order to facilitate mathematical tractability.

The concept of slotted time is implicit in Markov-based mobility models. At the end of each timeslot, the UE remains in the current cell with probability p or, alternatively, transits to an adjacent cell with probability $\frac{1-p}{6}$. Variations in the UE speed can be modelled by modifying the value of the parameter p.

Let us consider that the cell topology in Figure 1 is a TA. We define the concept of *cell ring* as a group of neighbouring cells where a UE can be found in a certain timeslot. The first ring is formed by a single cell located in the centre of the TA. The second ring is formed by all one-hop external neighbours of the first ring. The third ring is formed by all one-hop external neighbours of the second ring, and so on.

The concept of *inner* and *vertex* cells is also depicted in Figure 1. By definition, vertex and inner cells belong to the outermost ring of a Tracking Area. A vertex cell provides three exit points from the TA, while an inner cell provides two. This will be considered during $\bar{\lambda}_{TAU}$ calculation.

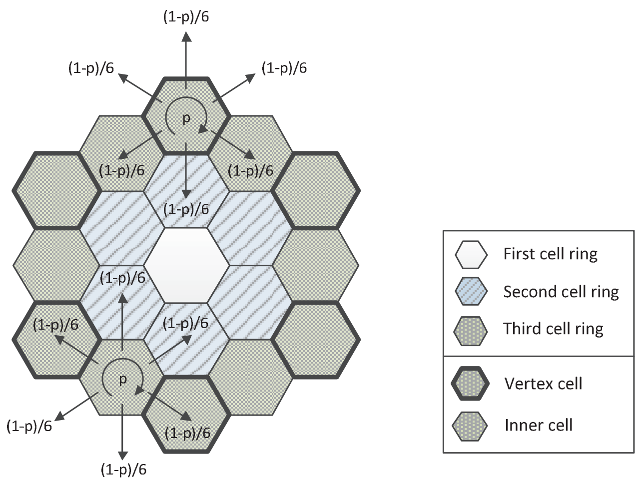

Figure 1 Markov-based mobility model in a hexagonal cell topology

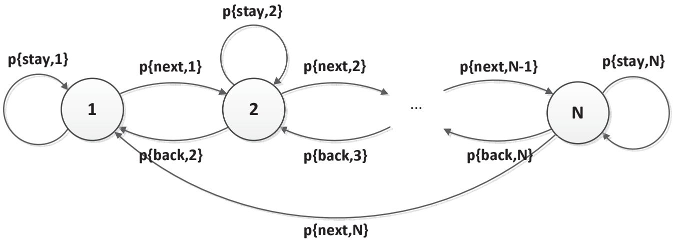

Figure 2 DTMC of a Markov-based mobility model with N cell rings

Markov-based mobility models can be mathematically described by discrete-time Markov chains (DTMCs). States in the DTMC represent the cell rings in the Tracking Area, as described in Figure 1. Analogously, transitions between states are associated with the probability of a UE staying in the current cell ring or moving (outwards or inwards) to an adjacent one. Figure 2 depicts the DTMC of a Markov-based mobility model in a hexagonal cell topology formed by N cell rings.

The values *p{stay,i}*, *p{next,i}*, and *p{back,i}* correspond to the probabilities of staying at, moving outwards from, and moving inwards from ring *i*, respectively. According to the cell topology in Figure 1, these probabilities can be calculated as:

$$p\{stay,i\} = p + 2p'$$

$$p\{next,i\} = p\{vertex,i\} \cdot 3p' + p\{inner,i\} \cdot 2p'$$

$$p\{back,i\} = p\{vertex,i\} \cdot p' + p\{inner,i\} \cdot 2p'$$

Where:

$$p' = p\{UE\ crossing\ a\ cell\ boundary\} = \frac{1-p}{6}$$

$$p\{vertex,i\} = \frac{1}{i-1}$$

$$p\{inner,i\} = 1 - p\{vertex,i\} = \frac{i-2}{i-1}$$

Once all transition probabilities have been determined, we can calculate the one-step transition probability matrix of the DTMC ($\mathbf{P}_{mob}$). $\mathbf{P}_{mob}$ describes the evolution of the mobility model, as it contains all transition probabilities between DTMC states. We use $\mathbf{P}_{mob}$ to calculate the steady-state probability vector of the DTMC ($\boldsymbol{\pi}_{mob}$), i.e., the vector that contains the probabilities of finding a UE in each one of the cell rings in the TA. It can be proved that:

$$\boldsymbol{\pi}_{mob} = [\pi_{mob}(1)\ \dots\ \pi_{mob}(N)] = \boldsymbol{e} \cdot (\boldsymbol{P}_{mob} + \boldsymbol{E} - \boldsymbol{I})^{-1}$$

Where $\pi_{mob}(i)$ is the probability of a UE being in the *i*-th cell ring of the Tracking Area, **e** is a row vector of all ones, **E** is a matrix of all ones, and **I** is the identity matrix.

Once $\boldsymbol{\pi}_{mob}$ is known, we can calculate the probability of initiating a Tracking Area Update procedure in a TA formed by N cell rings as:

$$p\{TAU,N\} = \pi_{mob}(N) \cdot p\{next,N\}$$

Where $\pi_{mob}(N)$ is the probability of being in the outermost ring of a Tracking Area formed by N cell rings and $p\{next,N\}$ is the probability of moving outwards from that ring.

Once $p\{TAU,N\}$ is known, we can calculate the average TAU arrival rate in a Tracking Area formed by N cell rings ($\bar{\lambda}_{TAU,N}$). In order to do so, let us consider the TAU Request arrival diagram in Figure 3.

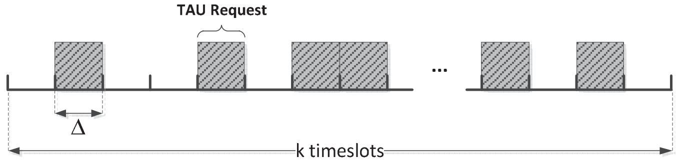

Figure 3 TAU Request arrival diagram

The average number of TAU arrivals in *k* timeslots can be calculated as:

$$\bar{N}_{TAU,k} = \sum_{i=1}^{k} p\{TAU,N\} = k \cdot p\{TAU,N\}$$

If the timeslot duration is Δ seconds, the average TAU arrival rate in a Tracking Area formed by N cell rings is:

$$\bar{\lambda}_{TAU,N} = \lim_{k\to\infty}\left(\frac{\bar{N}_{TAU,k}}{k \cdot \Delta}\right) = \frac{p\{TAU,N\}}{\Delta}\ \left[{}^{arrivals}/_{s}\right]$$

B. Self-Organized Tracking Area List Mechanism

The self-organized TAL mechanism is built on top of the standard 3GPP TAU procedure. This is done to comply with 3GPP Technical Specifications. First, the MME monitors the arrival rate of TAU Request messages from the UE in order to determine its mobility state. Secondly, the MME updates the UE-specific Tracking Area List by increasing, keeping, or reducing the number of rings in the TAL according to the mobility state and the paging arrival rate. Finally, the MME sends the new TAL to the UE in the TAU Accept message.

The self-organized mechanism combines static and dynamic TAL management depending on the UE mobility state. Thus, TALs are kept static until the location signalling traffic reaches a certain threshold. Past this *activation point*, the MME enables dynamic TAL management in order to reduce the overall location signalling traffic in the network. To further understand this behaviour, the concept of *stages* must be introduced. In stage 1, UEs are registered to Tracking Area Lists formed by a single cell ring. In stage 2, UEs are registered to TALs formed by two cell rings. In stage 3, TALs are formed by 3 cell rings, and so on.

In order to design an analytical model for the self-organized mechanism, some assumptions must be made. First, we assume that the NoF is a hexagonal cell structure formed by concentric rings, as described in Figure 1. Secondly, we assume that all TAs in the NoF are formed by a single femtocell. This allows MMEs to treat femtocells as TAs when managing Tracking Area Lists. Finally, we assume that UEs generate TAU Request messages according to a Poisson process with rate $\bar{\lambda}_{TAU,i}$, where *i* denotes the number of cell rings in the *i*-th stage of the self-organized TAL mechanism.

On the MME side, two mobility management timers (T1, T2) have been introduced in order to determine the mobility state of the UE. Timers are a common mechanism in 3GPP systems. Both UEs and MMEs use them to trigger signalling procedures, manage transitions between Radio Resource Control (RRC) states, monitor UE activity, release voice and data connections, control authentication protocols, etc. Some examples of 3GPP mobility management timers are T3412 (to trigger periodic TAU procedures), T3311 (to restart the attach procedure with the network) or T303 (to clear a voice call) [13].

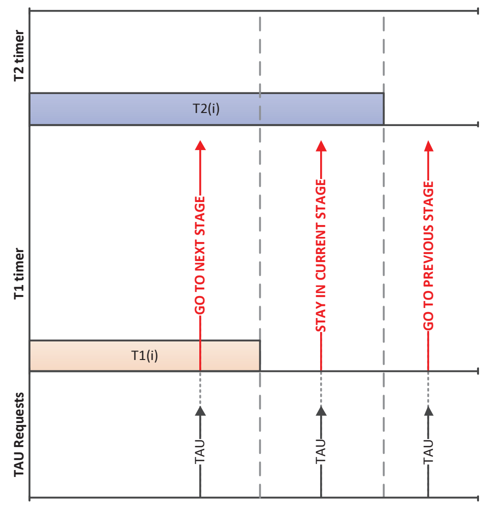

Figure 4 Transition events in the self-organized TAL mechanism

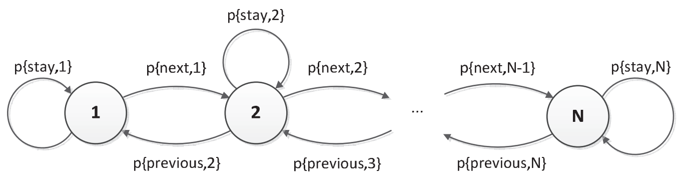

Figure 5 DTMC of a self-organized TAL mechanism with N stages

In each stage of the self-organized TAL mechanism, T1 and T2 are initialized to different values, namely *T1(i)* and *T2(i)*, where *i* denotes the stage. Thus, *T1(i)* controls transitions from the current to the next stage, while *T2(i)* controls transitions from the current to the previous stage. All possible transition events (*next*, *stay*, *previous*) are illustrated in Figure 4. The stage transition algorithm is described below:

- If the MME receives a TAU Request message before *T1(i)* expires, the mechanism transits to the next stage. This corresponds to a UE that is moving too fast for the TAL size in the *i*-th stage.
- If the MME receives a TAU Request message after *T1(i)* expires and before *T2(i)* expires, the mechanism remains in the current stage. This corresponds to a UE that is moving at well-suited speed for the TAL size in the *i*-th stage.
- If the MME receives a TAU Request message after *T2(i)* expires, the mechanism transits to the previous stage. This corresponds to a UE moving too slowly for the TAL size in the *i*-th stage.

After executing the stage transition algorithm, the MME updates the corresponding Tracking Area List and sends it back to the UE encapsulated in the TAU Accept message, as described in [3].

The self-organized TAL mechanism can be mathematically described by a DTMC. States in the DTMC correspond to the stages in the mechanism. Analogously, transitions between states are associated with the probability of staying in the current stage or moving (forward or backwards) to an adjacent stage. Figure 5 depicts the DTMC of a self-organized TAL mechanism with N stages.

In order to characterize the DTMC, we need to calculate *p{next,i}*, *p{previous,i}*, *p{stay,i}* for all stages in the system. Since TAU Request arrivals in each stage follow a Poisson process with arrival rate $\bar{\lambda}_{TAU,i}$, the transition probabilities can be calculated as:

$$p\{next,i\} = 1 - p\{no\ TAU\ arrivals\ during\ T1(i)\} = = 1 - e^{-\lambda_{TAU,i} \cdot T1(i)}$$

$$p\{previous,i\} = p\{no\ TAU\ arrivals\ during\ T2(i)\} = = e^{-\lambda_{TAU,i} \cdot T2(i)}$$

$$p\{stay,i\} = 1 - p\{next,i\} - p\{previous,i\}$$

Once all transition probabilities have been determined, we can calculate the one-step transition probability matrix of the DTMC ($\mathbf{P}_{self}$). As shown in Section IV.A, the steady-state probability vector ($\boldsymbol{\pi}_{self}$) can be calculated as:

$$\boldsymbol{\pi_{self}} = [\pi_{self}(1)\ \dots\ \pi_{self}(N)] = \boldsymbol{e} \cdot \left(\boldsymbol{P_{self}} + \boldsymbol{E} - \boldsymbol{I}\right)^{-1}$$

The self-organized TAL mechanism is fully characterized by $\boldsymbol{\pi_{self}}$, as it contains the probabilities of finding the system in each one of the N stages.

V. Performance Evaluation

In this section we evaluate the performance of the self-organized TAL mechanism against that of a conventional (static) TAL mechanism. For both schemes, we define the following *signalling cost function* per UE:

$$C_{tot} = p\{paging\} \cdot \bar{N}_{cells} \cdot c_p + p\{TAU\} \cdot c_{tau}$$

Where $p\{paging\}$ is the probability of a paging arrival in a timeslot, $\bar{N}_{cells}$ is the average number of cells in the Tracking Area List (static or dynamic) at a given instant, c_p is the signalling cost of a single paging operation, $p\{TAU\}$ is the probability of a TAU arrival in a timeslot, and c_{tau} is the signalling cost of a single TAU operation. In cellular networks, a TAU operation generates significantly more signalling traffic than a paging operation. In this paper we have assumed a signalling ratio $\alpha = \frac{c_{tau}}{c_p} = 10$, which is a common value in the literature [14], [15], [16]. By normalizing the expression of C_{tot} to c_p we obtain the *normalized signalling cost function*:

$$C_{norm} = \frac{C_{tot}}{c_p} = p\{paging\} \cdot \bar{N}_{cells} + \alpha \cdot p\{TAU\}$$

We want to evaluate C_{norm} as a function of the UE speed for both the conventional and self-organized mechanisms. As described in Section IV.A, speed variations can be modelled by modifying the value of *p* in the Markov-based mobility model. Thus, low speeds correspond to values of *p* closer to 1, while high speeds correspond to values of *p* closer to 0.

The performance of the self-organized TAL mechanism depends on the values of T1 and T2 in each stage of the system. In order to find the timer values that minimize the overall location signalling traffic, we have used a sequential quadratic programming solver (SQP). The output of the SQP is a pair of vectors:

$$\mathbf{T1_{opt}} = [\mathrm{T1}_{opt}(1)\ \mathrm{T1}_{opt}(2)\ \dots\ \mathrm{T1}_{opt}(N)]$$

$$\mathbf{T2_{opt}} = [\mathrm{T2}_{opt}(1)\ \mathrm{T2}_{opt}(2)\ \dots\ \mathrm{T2}_{opt}(N)]$$

Where $\mathbf{T1}_{opt}$ and $\mathbf{T2}_{opt}$ contain the values of timers T1 and T2 that minimize C_{norm} in each stage of the self-organized mechanism.

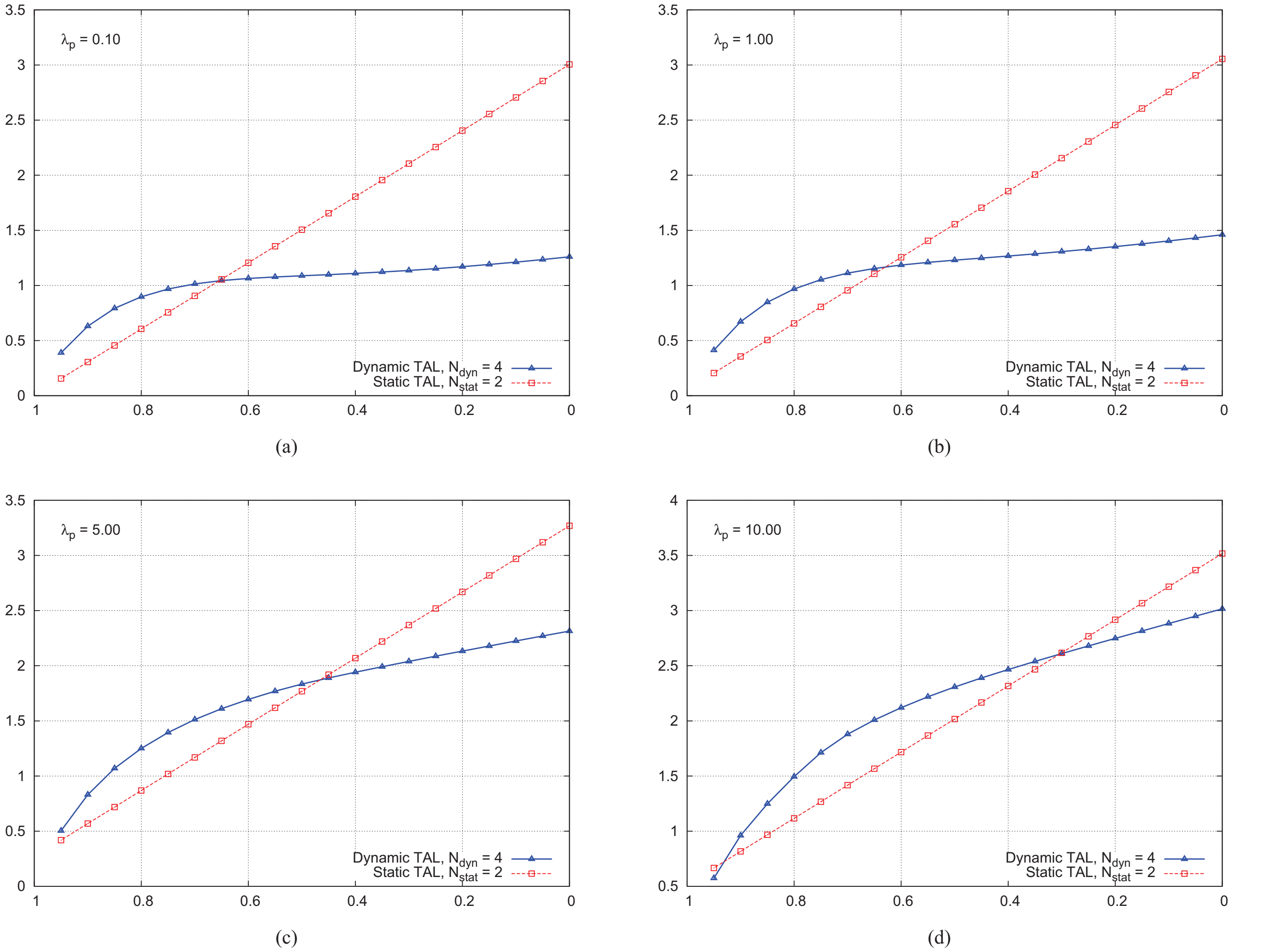

Figure 6 Normalized signalling cost function vs. probability of UE staying in current cell for different paging arrival rates

Numerical values for paging arrival rates (λ_p) and signalling ratio (α) have been taken from the literature [11], [14], [15], [16]. The static TAL size in the conventional mechanism (N_{stat}) has been set to 2 cell rings. Analogously, the maximum number of rings in a dynamic TAL (N_{dyn}) has been set to 4. The maximum femtocell transmission radius (r) is 200 m [17]. We have assumed pedestrian and vehicular users in an urban NoF scenario. Therefore, UEs travel at 0-50 km/h. Finally, the timeslot duration can be derived as:

$$\Delta = \frac{2r}{v_{max}}$$

Table I summarizes the numerical assumptions considered in the performance evaluation of the self-organized TAL mechanism.

Figure 6 shows the impact of UE speed on the normalized signalling cost function (C_{norm}) for different paging arrival rates. In general, dynamic Tracking Area Lists generate less location signalling traffic than static TALs for medium- to high-speed UEs. This reduction is significantly higher when UEs are subject to moderate paging. Since the cost of a single TAU operation is tenfold that of a paging operation, the self-organized TAL mechanism aims at minimizing C_{norm} by reducing the probability of TAU arrival for each UE.

TABLE I. NUMERICAL ASSUMPTIONS FOR PERFORMANCE EVALUATION

Parameter	Description	Values
λ_p	Paging arrival rate [*pagings/h*]	[0.1 – 10]
α	Signalling ratio	10
N_{stat}	Number of rings in a static TAL	2
N_{dyn}	Maximum number of rings in a dynamic TAL	4
v	UE speed [*km/h*]	0 - 50
r	Femtocell transmission radius [*m*]	200
Δ	Timeslot duration [*s*]	28.8

The intersections of the two curves in each figure determine the activation points of the self-organized mechanism. Thus, at speeds where static TALs generate less location signalling traffic than dynamic TALs, the self-organized mechanism keeps the TAL size constant. Once the activation point has been reached, the MME enables dynamic TAL management, hence reducing the overall location signalling traffic in the network. This switching strategy yields a significant reduction in location signalling traffic per UE, as shown in Table II.

TABLE II. REDUCTION IN LOCATION SIGNALLING TRAFFIC PER UE

λ_p	Reduction
0.1	39.45%
1	33.53%
5	13.21%
10	4.45%

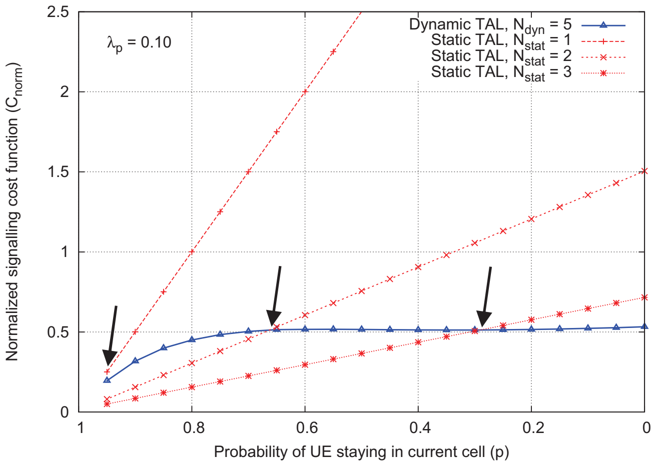

Figure 7 Normalized signalling cost function for different static TAL sizes

In commercial deployments, mobile network operators design static TAL layouts according to internal network planning criteria. The number of cells per TA and TAs per TAL depends on multiple parameters, such as user density, traffic patterns, UE mobility, etc. Figure 7 compares the performance of dynamic TAL management against that of static TAL management for different TAL sizes in a specific network scenario (other scenarios show a similar generic behaviour). The arrows in the figure correspond to the activation points of the self-organized TAL mechanism. Depending on the scenario and the network planning decisions, the use of dynamic TAL sizes may benefit UEs for different speed ranges. In any case, our mechanism is designed to improve the performance of the static (planned) layout by enabling dynamic TAL management if doing so reduces location signaling traffic.

VI. CONCLUSIONS

In this paper we have proposed a self-organized Tracking Area List mechanism that adapts the size of UE-specific TALs to the mobility state and the paging arrival rate of each terminal. Our scheme is particularly suitable for large-scale networks of femtocells, where handovers and cell reselections happen more frequently than in macrocell deployments. In addition, the self-organized TAL mechanism is fully compliant with 3GPP Technical Specifications, which facilitates its implementation in a commercial scenario. We have proposed an analytical model based on discrete-time Markov chains to evaluate the performance of the proposed mechanism against that of the conventional (static) TAL mechanism. The model shows how the self-organized mechanism improves the performance of the conventional mechanism in terms of location signalling traffic for different paging arrival rates. Furthermore, analytical results show that the proposed mechanism can generate up to a 39% less location signalling traffic per UE than the conventional mechanism.

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