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Reducing paging cost of tracking area list-based mobility management in LTE network

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Abstract In long-term evolution (LTE) network, service area is composed of tracking areas (TAs) lists (TALs) and a TAL includes a few neighbor TAs. In this paper, we consider paging schemes for TAL-based mobility management in LTE network. In TAL-based mobility management, whenever a user equipment (UE) enters a new TAL, it updates its location so that the current TA becomes the center TA of new TAL. We develop a mathematical model to analyze signaling cost of previous paging schemes for TAL-based mobility management. We then suggest new paging schemes to reduce paging cost. First, in order to mathematically analyze the performance of previous paging schemes, we use a Markov chain model based on 2-D random walk model. In our 2-D random walk model, unlike prior studies, the UE can move to one of four neighbor cells with equal probability to be more realistic. We also suggest new paging schemes to reduce the paging cost of previous paging schemes. With our analytical models, our paging schemes are found to be better than previous paging schemes in most cases. Various numerical results show that the proposed schemes are much more effective than previous paging schemes. These results suggest that the proposed schemes can be used effectively in the design and evaluation of mobility management in LTE network.

Keywords TAL-based mobility management · Paging · Location registration · Markov chain · 2-D random walk model

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1 Introduction

It is important to know the location of user equipment (UE) so that incoming calls can be delivered to UEs properly [2–7]. The network uses mobility management mechanism to keep location of the UE. Mobility management consists of two essential operations: location registration and paging. Location registration is the process through which the UE dynamically updates its location in network databases. Paging is a process through which the network broadcasts a paging message to all cells of current location area and pinpoints the cell where the UE currently resides when an incoming call arrives so that the incoming call can be delivered to the UE [9–15, 17].

Figure 1 shows a simple TAL structure in LTE network. In LTE network, mobility management entity (MME) is responsible for tracking locations of UEs. The MME is connected to a group of evolved Node Bs (eNBs). The radio coverage of eNB is called a cell. These cells are grouped into non-overlapped tracking areas (TAs) [1]. Some TAs are then grouped into a TA list (TAL). As shown in Fig. 1, TA 3 is composed of cells 5 and 6, while TA 3 is included in TAL 1.

Every eNB periodically broadcasts its TA identity (TAI). The UE receives this TAI and compares with its stored TAL. If the received TAI is not in its stored TAL, the UE executes the location update procedure to inform MME of its new location. The MME then allocates a new TAL to the UE. As shown in Fig. 1, if the UE in cell 8 moves to cell 9 and the received TAI (TA 5) is not found in TAL 1, then the UE updates its location because it is not in the TAL 1. The MME then allocates TAL 2 to the UE where TAL 2 = {TA 4, TA 5, TA 6}.

In TAL-based mobility management, whenever a UE enters a new TAL, it updates its location so that the TA of interacted cell becomes the center TA of the new TAL [5, 11, 12, 18]. This is called central policy. For example, if a UE in TAL 1 moves to cell 9 from cell 8, then the UE updates its TAL in which TA 5 is the center TA of the new TAL 2. Note that allocated TALs might be overlapped in the central policy. For example, both TAL 1 and TAL 2 include TA 4 (Fig. 1).
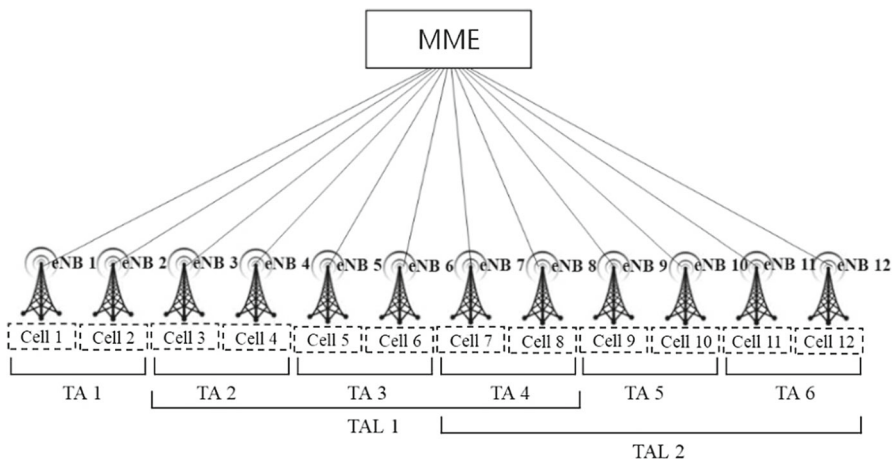

Fig. 1 TAL structure in LTE network

The central policy of TAL-based management evidently reduces ping-pong phenomenon, a main problem of zone-based mobility management that is mostly adopted in mobile cellular networks [9, 11, 12]. On the other hand, overlap of some TAs by the central policy may result in increment of paging cost compared to non-overlapping structure. Therefore, a good paging scheme is especially important for TAL-based management.

In this study, we propose new paging schemes to reduce paging cost. Our results show that, using our mathematical model, our proposed schemes can yield better performance than previous paging schemes under most situations.

The organization of this paper is as follows. Section 2 explains TAL-based mobility management and paging scheme with 2-D random walk mobility and proposes new paging schemes. In Sect. 3, a new mathematical model is presented to analyze paging cost for each scheme. In Sect. 4, numerical examples are presented. Lastly, conclusion is drawn in Sect. 5.

2 TAL-based mobility management and paging schemes

2.1 Network configuration

In our study, we consider a two-dimensional mesh cell configuration as shown in Fig. 2. In this figure, a square represents a cell. In this configuration, each cell has eight surrounding cells. There are only four adjoined neighbor cells.

Some studies have assumed that the UE moves to one of the eight neighbor cells in mesh cell configuration [10, 11]. In our random walk model, however, the UE moves to the four adjoined neighbor cells with equal probability (1/4).

In the previous studies, some have used 1-D model [12], while others have used 2-D model [10, 18] to analyze the performance of TAL-based mobility management. 1-D model is too simple to consider real situations. 2-D model is more realistic. However,
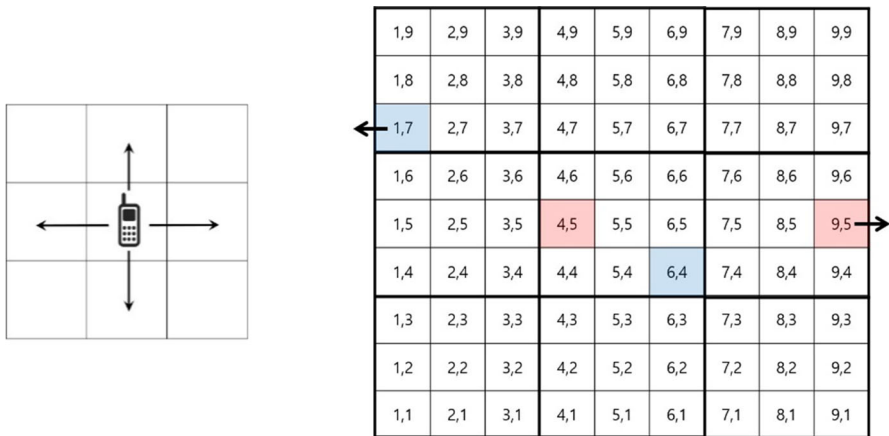

Fig. 2 A TAL in a mesh cell configuration ($N_C = N_T = 3 \times 3$)

some studies on 2-D model have only been performed by computer simulations [10, 11].

Let N_C be the number of cells in a TA, and let N_T be the number of TAs in a TAL. Figure 2 illustrates a TAL in a mesh cell configuration for TAL-based mobility management, where $N_C = N_T = 3 \times 3$. In this figure, a cell is labeled (x, y), where x is the column label and y is the row label. To simplify our discussion on the central policy mentioned in Sect. 1, we assume that N_T is an odd number.

Note that, due to the central policy, when the UE moves out of the current TAL, the entered TA is reset as the center TA of the new TAL. For example, as shown in Fig. 2, when the UE moves from cell (9, 5) to a new TAL, the entered cell is reset as cell (4, 5) in the new center TA of the new TAL. Similarly, if the UE moves from cell (1, 7) to a new TAL, the entered cell is reset as cell (6, 4) in the new center TA of the new TAL.

2.2 Previous paging schemes

When an incoming call to a UE arrives, the network searches the called UE. The network sends paging messages to all cells of the UE's TAL to search the UE. This may incur high cost that significantly consumes limited radio resources. Various paging schemes have been proposed to reduce the paging cost [12]. In these schemes, an interacted cell refers to a cell in which the UE receives a call or performs a location registration.

- *Scheme Cell-TAL* (*CT*) When an incoming call arrives, the MME sends paging messages to the last interacted cell in the TAL. If the MME does not receive response within a timeout period, the MME sends paging messages to all cells in the TAL.
- *Scheme TA-TAL* (*TT*) When an incoming call arrives, the MME sends paging messages to the TA of the last interacted cell. If the MME does not receive response within a timeout period, the MME sends paging messages to all cells in the TAL.
- *Scheme Cell-TA-TAL* (*CTT*) When an incoming call arrives, the MME first sends paging message to the last interacted cell to alert the UE. If the MME does not receive response within a timeout period, the MME sends paging messages to the TA of the last interacted cell. If the MME still receives no response from the UE, the MME then sends paging messages to all cells in the TAL.

We define these three schemes shown above as previous paging schemes. Some studies have analyzed the performance of these paging schemes. Liou et al. have considered 1-D random walk model to compare various types of previous paging schemes [12]. Another previous study has suggested a dynamic paging scheme, in which three paging schemes are combined to minimize the paging cost [10]. However, its performance has only been demonstrated by computer simulations.

2.3 New paging schemes

As described above, three kinds of paging schemes (*CT*, *TT*, and *CTT*) have been proposed. However, those schemes seem to have large paging cost because of over-

lapping of paging areas. Another problem of these schemes is that 3-step paging they assume is unrealistic since it is difficult for real networks to allow more than 2-step paging due to long paging delay.

To alleviate these problems, we proposed the following new paging schemes:

- *Scheme n TA-remaining TAs* (*nTA*) When an incoming call arrives, the MME sends paging messages to n (≥ 1) TAs, including the TA of the last interacted cell. If the MME does not receive a response within a timeout period, the MME sends paging messages to all TAs in the TAL except n paged TAs.
- *Scheme n^* TA-remaining TAs* (*dTA*) When an incoming call arrives, the MME sends paging messages to n^* (≥ 1) TAs, including the TA of the last interacted cell, where n^* is the optimum value of n that produces the minimum paging cost of *nTA*. If the MME does not receive a response within a timeout period, the MME sends paging messages to all TAs in the TAL except n^* paged TAs.

In *nTA* scheme, according to the number of TAs paged first, n, there can be 1*TA*, 2*TA*, 3*TA*, and so on. In other words, *nTA* scheme is not a single scheme. Instead, it includes many schemes such as 1*TA*, 2*TA*, 3*TA*, and so on.

In *dTA* scheme, the MME dynamically selects the best paging scheme in real time based on the up-to-date history for call-to-mobility ratio. Specially, the MME computes the average number of paged cells for 1*TA*, 2*TA*, 3*TA*, and so on in the specified number of incoming calls to determine the optimal n^* for the next incoming call. Note that n^* depends on situations. It is not easy to determine the optimal n^* in a specific situation.

In this study, for the convenience of analysis, we assumed that a UE could estimate the optimal n^* based on the UE's up-to-date history for call-to-mobility ratio and that the estimation would be correct with a probability of $1-p$. We also assumed that, even when $n^*=n$, n^* could be estimated incorrectly as $n-1$ with a probability of $p/2$ or as $n+1$ with a probability of $p/2$. For example, when $n^*=2$, n^* is estimated incorrectly as 1 with probability of $p/2$ or as 3 with probability of $p/2$. Even when the probability that the estimation was incorrect and p was very large (for example $p=0.5$), the *dTA* scheme still showed good performance.

In our scheme, the paging procedure is composed of two steps. Therefore, we only consider *TT* and *CT* schemes among the three previous schemes to compare with our schemes because they are also performed in two steps.

3 Analytical model

Now, let us analyze performances of the previous paging schemes and our schemes to compare their performances. This section presents a mathematical model for the previous paging schemes and our schemes. First we will introduce some notations and assumptions.

Notations and assumptions

The following notations are defined to analyze the total signaling cost on radio channels.

$C_{P,S}$: total paging cost for an incoming call in the paging scheme S
V: unit signaling cost for paging one cell ($V=1$ is assumed in this study)
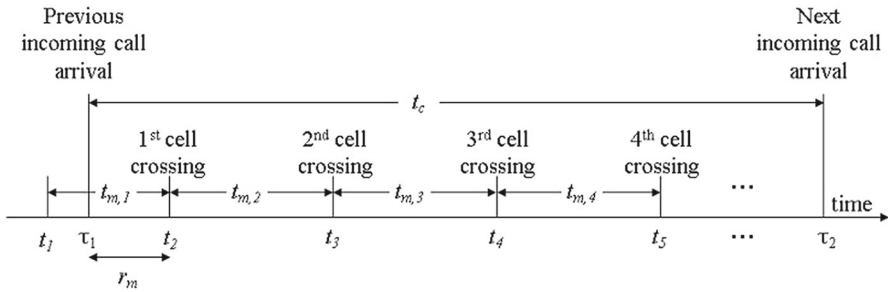
Fig. 3 Timing diagram between two incoming calls

N^2: number of cells in a TA (=number of TAs in a TAL in this study)

t_c: interval between two incoming calls

t_m: sojourn time in a cell

λ_c: arrival rate of incoming calls

$1/\lambda_m$: mean of sojourn time in a cell

ρ: call-to-mobility ratio (CMR), $\rho = \frac{\lambda_c}{\lambda_m}$

$f_m^*(s)$: Laplace–Stieltjes Transform for $t_m \left(= \int_{t=0}^{\infty} e^{-st} f_m(t)\, dt \right)$.

Figure 3 illustrates a timing diagram for cell crossings and incoming call arrivals. Suppose that the UE resides in a cell when the previous call arrives. After the call, UE visits another cell and resides in the i-th cell for a period $t_{m,i}$. Let r_m be the interval between the arrival of the previous call and the time when UE moves out of the cell. In this study, we assumed that call arrival interval t_c followed an exponential distribution with mean $\frac{1}{\lambda_c}$ and that the sojourn time in the i-th cell $t_{m,i}$ was independent and identically distributed with a general density function $f_m(t_m)$, mean $\frac{1}{\lambda_m}$, and the Laplace transform $f_m^*(s) = \int_{t=0}^{\infty} e^{-st} f_m(t)\, dt$. It was assumed that the UE would move to the four neighbor cells with same probability of 1/4.

Now we derive paging cost for various paging schemes. Figure 4 illustrates state-transition diagram for $N_C = N_T = 3 \times 3$ shown in Fig. 2. Even though there are 81 cells in the TAL in Fig. 2, it is sufficient to consider only 15 cells (in other words, 15 + 3 states) as shown in Fig. 3 since characteristics of some cells in the TAL are identical. For example, cells (1, 1), (1, 9), (9, 9), and (9, 1) have the same probabilistic characteristics. Cells (2, 5), (5, 8), (8, 5), and (5, 2) also have the same probabilistic characteristics. Therefore, we first calculated steady-state probability of each state in this reduced model. We then recalculated steady-state probabilities of all cells in original TAL shown in Fig. 2. Note that there are two types of transitions: transition by entering a cell and transition by a call generation.

In Fig. 4, state (i, j) for $i \leq j$ and $i, j = 1, 2, \ldots 5$ is the state that UE is in cell (i, j) through entering the cell. State (i', j') for $i' \leq j'$ and $i', j' = 4, 5$ is the state that the UE in a cell receives an incoming call and then the TA of the cell becomes the center TA of the new TAL where the cell is reset as the corresponding cell (i, j) of the center TA through a call generation (i.e., an implicit registration) for $i \leq j$ and $i, j = 4, 5$.

The TA of a border cell in the TAL can become the center TA of the new TAL by a regular registration. For example, if the UE in cell (1, 2) moves to the left cell, then the TA of the cell becomes the center TA of the new TAL. Note that the cell the UE
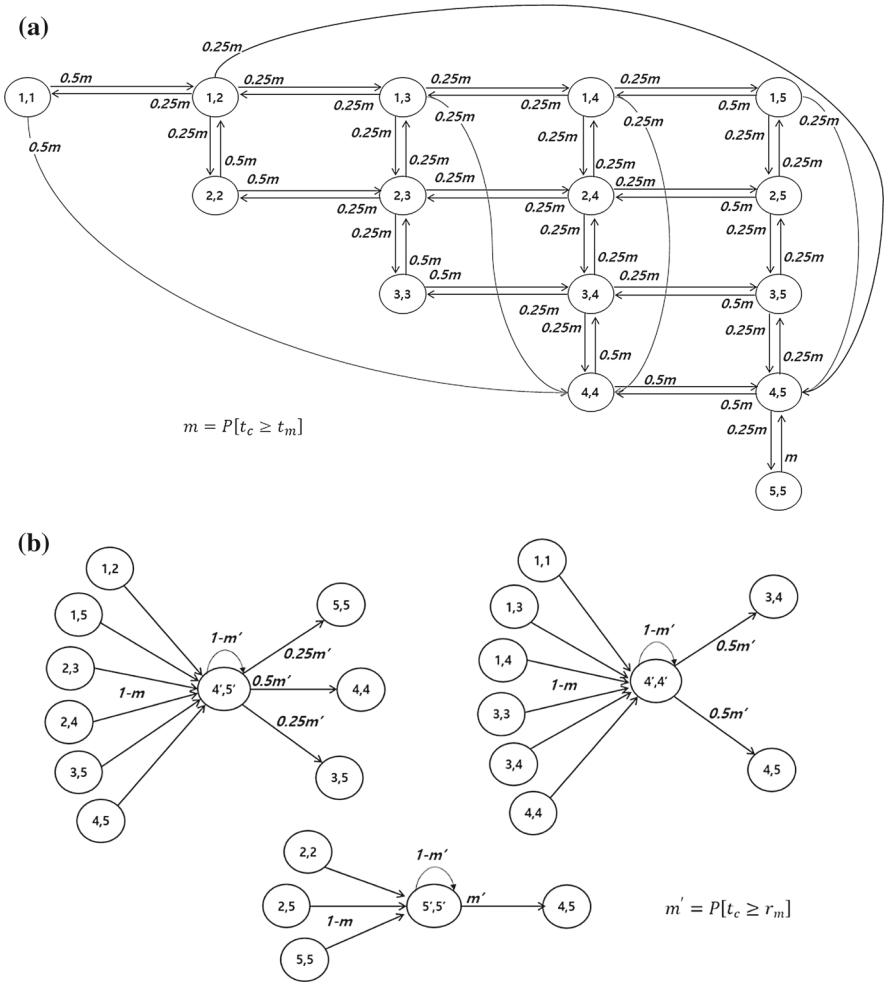
Fig. 4 State-transition diagram for $N_C = N_T = 3 \times 3$. **a** State-transition diagram except (i', j'). **b** State-transition diagram for (i', j')

enters becomes cell $(6, 5)$ of the new TAL. It is then reset as state $(4, 5)$ in our reduced model as shown in Fig. 4.

In addition, the TA of any cell in the TAL can become the center TA of the new TAL through an implicit registration. For example, if the UE in cell $(4, 2)$ receives an incoming call, then the TA of cell $(4, 2)$ becomes the center TA of the new TAL through an implicit registration. The cell is then reset as state $(4', 5')$ in our reduced model as shown in Fig. 4.

As shown in Fig. 4, the UE moves from any state to the four neighbor TAs with probability of 0.25 m or 0.25 m'. The transition probability m is the probability that UE in the cell (i, j) moves to the neighbor cells before an incoming call arrives. It can be obtained as following:

$$m = P\left[t_c \geq t_m\right] = \int_{t_m=0}^{\infty} \int_{t_c=t_m}^{\infty} \lambda_c e^{-\lambda_c t_c} f_m\left(t_m\right) \mathrm{d}t_m \mathrm{d}t_c = f_m^*\left(\lambda_c\right). \quad (1)$$

For example, UE in the state $(2, 3)$ can move to one of the neighbor cell $(2, 2)$, $(1, 3)$, $(2, 4)$, or $(3, 3)$ with a probability of 0.25 m before an incoming call arrives.

Note that the transition probability from any state to state (i', j') is $1 - m = P\left[t_c < t_m\right] = 1 - f_m^*\left(\lambda_c\right)$.

Similarly, the transition probability m' is the probability that UE in state (i', j') moves to the neighbor cells before an incoming call arrives. It can be obtained as following:

$$m' = P\left[t_c \geq r_m\right] = \int_{r_m}^{\infty} \int_{t_c=r_m}^{\infty} \lambda_c e^{-\lambda_c t_c} f_r\left(r_m\right) \mathrm{d}t_c \mathrm{d}r_m = \frac{\lambda_m}{\lambda_c}\left(1 - f_m^*\left(\lambda_c\right)\right) \quad (2)$$

where r_m is a random variable which indicates residual time in the current TA. For example, UE in state $(4', 5')$ can move to one of the neighbor cell $(3, 5)$, $(4, 6)$, $(5, 5)$, or $(4, 4)$ with a probability of 0.25 m' before an incoming call arrives. Note that, since cell $(4, 6)$ in Fig. 2 is reset as state $(4, 4)$ in our reduced model in Fig. 4, UE in state $(4', 5')$ can move to state $(3, 5)$ or $(5, 5)$ with a probability 0.25 m' or move to state $(4, 4)$ with a probability of 0.5 m' as shown in Fig. 4b.

In addition, the transition probability from state (i', j') to state (i', j') is $1 - m' = 1 - P\left[t_c \geq r_m\right] = P\left[t_c < r_m\right]$.

Let $\pi_{(i, j)}$ and $\pi_{(i', j')}$ be steady-state probabilities of state (i, j) and state (i', j'), respectively. We can obtain steady-state probability π for transition probability P using the following balanced equations [8, 16]:

$$\pi P = \pi, \quad \sum_{j=1}^{5} \sum_{i \leq j} \pi_{(i, j)} + \sum_{j'=4}^{5} \sum_{i' \leq j'} \pi_{(i', j')} = 1 \quad (3)$$

After these steady-state probabilities in our reduced model are obtained, we can recalculate steady-state probabilities of all cells in original TAL considering the number of cells with the same probabilistic characteristics, which is simple.

Note that, in our example, in cases of cell $(1, 5)$, $(2, 5)$, $(3, 5)$, $(4, 5)$, $(1, 1)$, $(2, 2)$, $(3, 3)$, or $(4, 4)$, the number of cells with the same probabilistic characteristics is 4. In cases of cell $(1, 4)$, $(2, 4)$, $(3, 4)$, $(1, 3)$, $(2, 3)$, or $(1, 2)$, the number of cells with the same probabilistic characteristics is 8.

As results, for example, if $\pi_{(2,5)} = 0.04$ is obtained, since cells $(5, 8)$, $(8, 5)$, and $(5, 2)$ have the same probabilistic characteristics as cell $(2, 5)$ (i.e., the number of cells with the same probabilistic characteristics is 4), we can recalculate all steady-state probabilities of cells $(2, 5)$, $(5, 8)$, $(8, 5)$, and $(5, 2)$ as $0.01 = 0.04/4$ (i.e., $\pi_{(2,5)} = \pi_{(5,8)} = \pi_{(8,5)} = \pi_{(5,2)} = 0.01$).

Through recalculation of all steady-state probabilities considering the number of cells with the same probabilistic characteristics, we can finally obtain all steady-state probabilities of all states in original TAL.

To derive paging cost, we define the paging cost of scheme S as $C_{P,S}$, where $S = \{CT, TT, nTA, dTA\}$. The paging cost can be derived by multiplying the number of cells to page by paging cost per cell. In 2-step paging schemes, the number of cells to page for an incoming call is the sum of cases where the system has correct location information (first paging success or *hit*) and incorrect location information (first paging failure or *miss*). In our study, we assume that the paging cost for one cell is 1.

In our TAL structure, we assume that there are $N_C = N \times N$ cells and $N_T = N \times N$ TAs where N is an odd number. That is, we assume that there are $N_T = N^2 \times N^2$ cells.

As mentioned earlier, the TA of a border cell in the TAL can become the center TA of the new TAL by a regular registration. In addition, any cell in TAL can become cell of the center TA of the new TAL by an implicit registration.

For notational convenience, let

$$
p_{RR}^{cTA} = \sum_{i=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \sum_{j=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \pi_{(i,j)}, \quad p_{IR}^{cTA} = \sum_{i'=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \sum_{j'=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \pi_{(i',j')} \quad (4)
$$

Then, p_{RR}^{cTA} is the probability that a UE is in the center TA through entering a cell and p_{IR}^{cTA} is the probability that a UE is in the center TA through a call generation. The probability that the UE resides in the TA of the last interacted cell when an incoming call arrives is

$$
P[\text{hit in } TT] = \sum_{i=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \sum_{j=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \pi_{(i,j)} + \sum_{i'=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \sum_{j'=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \pi_{(i',j')}
$$
$$
= p_{RR}^{cTA} + p_{IR}^{cTA} \quad (5)
$$

For example, when $N=3$, $P[\text{hit in } TT] = \sum_{i=4}^{6} \sum_{j=4}^{6} \pi_{(i,j)} + \sum_{i'=4}^{6} \sum_{j'=4}^{6} \pi_{(i',j')}$.

As a result, the probability that the UE resides in the last interacted cell when an incoming call arrives is

$$
P[\text{hit in } CT] \approx \frac{1}{N^2} \sum_{i=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \sum_{j=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \pi_{(i,j)} + \frac{1}{N^2} \sum_{i'=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \sum_{j'=\frac{N(N-1)}{2}+1}^{\frac{N(N+1)}{2}} \pi_{(i',j')}
$$
$$
= \frac{1}{N^2} p_{RR}^{cTA} + \frac{1}{N^2} p_{IR}^{cTA} \quad (6)
$$

For example, when $N=3$, $P[\text{hit in } CT] \approx \frac{1}{9} \sum_{i=4}^{6} \sum_{j=4}^{6} \pi_{(i,j)} + \frac{1}{9} \sum_{i'=4}^{6} \sum_{j'=4}^{6} \pi_{(i',j')}$.

Finally, the paging cost of each scheme can be written as follows:

$$C_{P,CT} = 1 \times P\,[\text{hit in } CT] + N^4 \times P\,[\text{miss in } CT]$$

$$\approx \left(1 - N^4\right) \times \left[\frac{1}{N^2}\, p_{RR}^{cTA} + \frac{1}{N^2}\, p_{IR}^{cTA}\right] + N^4$$

$$C_{P,TT} = 1 \times P\,[\text{hit in } TT] + N^2 \times P\,[\text{miss in } TT]$$

$$= \left(1 - N^2\right) \times \left[p_{RR}^{cTA} + p_{IR}^{cTA}\right] + N^2$$

$$C_{P,nTA} = n \times P\,[\text{hit in } nTA] + \left(N^2 - n\right) \times P\,[\text{miss in } nTA]$$

$$= \left(2n - N^2\right) \times \left[p_{RR}^{cTA} + p_{IR}^{cTA} + \text{limiting probabilities of } (n-1)\,\text{TAs nearest to center TA}\right] + \left(N^2 - n\right)$$

$$C_{P,dTA} = (1 - p) \times \left\{ n^* \times P\left[\text{hit in } nTA \text{ with } n = n^*\right] + \left(N^2 - n^*\right) \times P\left[\text{miss in } nTA \text{ with } n = n^*\right]\right\}$$

$$+ (p/2) \times \left\{ (n^* - 1) \times P\left[\text{hit in } nTA \text{ with } n = n^* - 1\right]\right.$$

$$+ \left(N^2 - n^* + 1\right) \times P\left[\text{miss in } nTA \text{ with } n = n^* - 1\right]\right\}$$

$$+ (p/2) \times \left\{(n^* + 1) \times P\left[\text{hit in } nTA \text{ with } n = n^* + 1\right]\right.$$

$$+ \left(N^2 - n^* - 1\right) \times P\left[\text{miss n } nTA \text{ with } n = n^* + 1\right]\right\} \qquad (7)$$

where n^* is the optimal number of first paged TAs that minimize $C_{P,nTA}$.

Note that, in $C_{P,nTA}$, to obtain limiting probabilities of $(n-1)$ TAs nearest to center TA, $(n-1)$ TAs that are nearest to center TA are selected first. For example, when $n=3$, any two TAs among four neighbor TAs of center TA can be selected since the four neighbor TAs of center TA have the same probabilistic characteristics because of our random walk mobility model.

Also note that, when $n^* = 2$ and $p=0.2$,

$$C_{P,dTA} = (0.8) \times \left\{2 \times P\,[\text{hit in } 2TA] + \left(N^2 - 2\right) \times P\,[\text{miss in } 2TA]\right\}$$

$$+ (0.1) \times \left\{(1) \times P\,[\text{hit in } 1TA] + \left(N^2 - 1\right) \times P\,[\text{miss in } 1TA]\right\}$$

$$+ (0.1) \times \left\{(3) \times P\,[\text{hit in } 3TA] + \left(N^2 - 4\right) \times P\,[\text{miss in } 3TA]\right\}$$

4 Numerical results

In this section, using our mathematical model in Sect. 3, we compare performances of paging schemes. We consider mesh cell configuration. Therefore, each cell has four neighbor cells. We consider TAL's size $N_C = 3 \times 3$, $N_T = 3 \times 3$, as shown in Fig. 2. The following are assumed [3, 5, 10–12]:

- A UE receives a call in an hour ($\lambda_c = 1$).
- The number of cells a UE enters in an hour is Poisson distributed with a mean of 4 ($\lambda_m = 4$).
- The paging cost for one cell, P, is 1 ($P=1$).
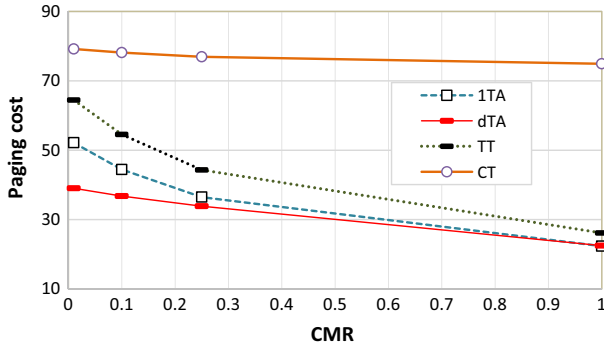- The probability (p) that the estimation for n^* is incorrect is 0.1 ($p=0.1$).

Fig. 5 The paging cost of each paging scheme for various CMRs ($p = 0.1$)

4.1 Paging cost for various CMRs

First, let us compare performances of previous paging schemes and the proposed schemes as λ_c/λ_m varies. Figure 5 shows paging costs of *CT*, *TT*, 1*TA*, and *dTA* schemes as call-to-mobility (CMR $= \lambda_c/\lambda_m$) ratio varies from 0.01 to 1.0. CMR $= \lambda_c/\lambda_m = 0.1$. This means that a UE enters zones 10 times between two calls.

As λ_c/λ_m decreases (i.e., cell crossing increases during t_c), the UE may be far away from the last interacted cells. As a result, higher paging traffic is expected since it is difficult that the first paging is successful. As shown in Fig. 5, as λ_c/λ_m decreases, paging cost increases since UE is far from the last interacted cell. Among the four schemes as shown in Fig. 5, *CT* scheme shows very bad performance even when CMR $= 0.01$. *TT* shows worse performance compared to *dTA* or 1*TA*. Our suggested *dTA* shows good performance compared to the other schemes under most situations. Note that, in $C_{P,nTA}$, since P [hit in CT] $\geq \frac{1}{N^2} p_{RR}^{cTA} + \frac{1}{N^2} p_{IR}^{cTA} = P$ [UE is in a specific cell of center TA], P [hit in CT] $\approx \frac{1}{N^2} p_{RR}^{cTA} + \frac{1}{N^2} p_{IR}^{cTA}$ makes $C_{P,CT}$ better (or less) than the real value. Nevertheless, $C_{P,CT}$ shows worse performance compared to other schemes. This means that CT is really bad. Here after, we will drop CT since its performance is too bad to be compared with other schemes.

Figure 6 shows paging costs of 1*TA*, 2*TA*, 3*TA*, and *dTA* schemes as call-to-mobility (CMR $= \lambda_c/\lambda_m$) ratio varies from 0.01 to 1.0. When CMR $= 1.0$, 1*TA* has the least paging cost. As CMR decreases, the optimal number of TAs paged firstly increases. As a result, when CMR $= 0.01$, 4*TA* has the least paging cost. However, 4*TA* is not presented in the table for convenience. Since it is assumed that UE's estimation of optimal n^* will be correct with probability $1 - p$, *dTA* always has slightly larger paging cost than the optimal paging cost. For example, when CMR $= 0.25$, 2*TA* has the least paging cost at 33.72. The paging cost of *dTA* is 33.87 ($= 33.72 \times 0.9 + 36.46 \times 0.05 + 34.09 \times 0.05$), which is slightly larger than 33.72. Note that the difference between the optimal paging cost and paging cost of *dTA* is very small (1–2% at the most) in every CMR (Table 1).
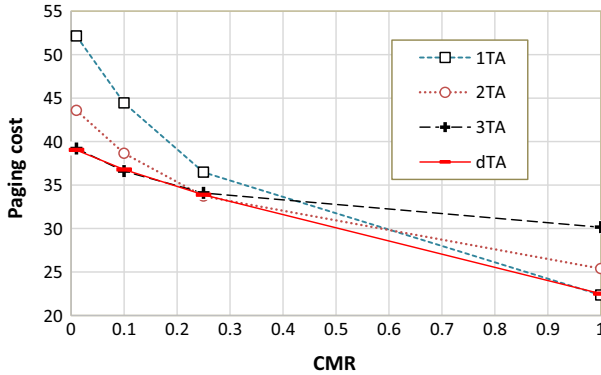
Fig. 6 Paging cost and difference ratio of paging schemes

Table 1 Paging cost and difference ratio of paging schemes

CMR	Scheme			
	1TA	2TA	3TA	dTA
1.00	**22.34**	25.39	30.15	**22.49**
0.25	36.46	**33.72**	34.09	**33.87**
0.10	44.43	38.65	**36.59**	**36.78**
0.01	52.14	43.57	39.20	**39.03**

Bold values indicate minimum for each CMR

4.2 Paging cost for various variances

Even though it is assumed that the sojourn time in a cell is exponentially distributed for computational convenience as described in Sect. 3, it is possible to consider any type of distribution for sojourn time in a cell [3, 9]. Let us assume that the sojourn time in a cell follows a Gamma distribution to examine paging costs for various variances.

Figure 7 shows paging costs of *TT*, 1*TA*, and *dTA* schemes as variance varies from 0.1 to 10. As variance decreases, it is expected that the optimal number of TAs paged firstly will decrease. As a result, when variance is very small, *dTA* is 1*TA*. On the other hand, as variance increases, it is expected that the optimal number of TAs paged firstly increases. Therefore, when variance is 10, *dTA* is not 1*TA*, but 2*TA* in our circumstances.

4.3 Paging cost for various *p*

Figure 8 shows paging costs of *dTA* schemes as *p* varies from 0.0 to 0.5. When *p* =0.0, it means that a UE can estimate the optimal n^* with a probability of 1. As *p* increases, the difference between the optimal paging cost and the paging cost of *dTA* also increases. However, the difference is very small. When the probability (*p*) that the estimation for n^* is incorrect is 0.1 (*p*=0.1), the paging cost is only larger than
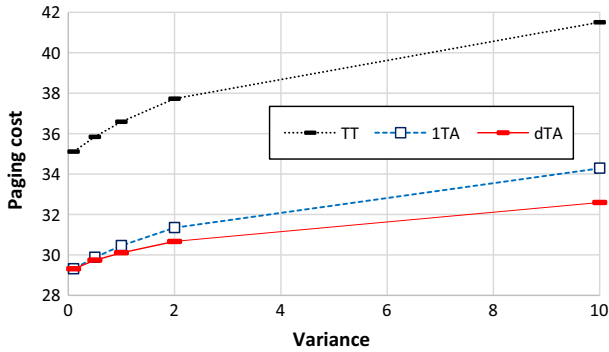
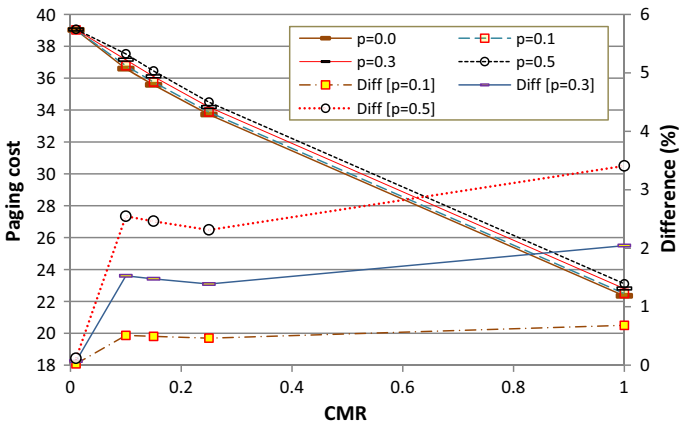**Fig. 7** The paging cost of each paging scheme for various variances (CMR = 0.5)

Fig. 8 The paging cost of each paging scheme for various p values

Table 2 The paging cost of each paging scheme for various p values

p	CMR				
	0.01	0.10	0.15	0.25	1.00
$p=0.0$	39.02	36.59	35.58	33.72	22.34
$p=0.1$	39.03	36.78	35.75	33.87	22.49
$p=0.3$	39.05	37.15	36.10	34.19	22.80
$p=0.5$	39.06	37.52	36.45	34.50	23.10
Diff [$p=0.1$] (%)	0.02	0.51	0.49	0.46	0.68
Diff [$p=0.3$] (%)	0.07	1.53	1.48	1.39	2.04
Diff [$p=0.5$] (%)	0.12	2.55	2.46	2.31	3.41

the optimal paging cost by less than 1%. Even when the estimation for n^* is incorrect with probability of 0.5 ($p=0.5$), the paging cost is only larger than the optimal paging cost by less than 3.5% at most. Note that, when CMR is very small, the paging cost is very large. It may cause some problems on radio channel. However, the paging cost of *dTA* is almost the same as the optimal paging cost, making *dTA* unique (Table 2).

Numerical results for various situations show that, when a UE enters cells frequently (in other words, CMR is small), the paging cost increases and 3*TA* outperforms 2*TA* and 1*TA* for CMR ≤ 0.1, which indicates $n^* = 3$. On the other hand, when a UE enters cells infrequently (in other words, CMR is large), the paging cost decreases and 1*TA* outperforms 2*TA* and 3*TA* for CMR ≥ 1.0, which indicates $n^* = 1$. Note that the optimal n^* varies according to the mobility pattern of a UE. Therefore, it can be expected that *dTA* has good performance. In fact, various numerical results verify that, even though there is a little difference from optimal paging cost, *dTA* consistently shows very good performance. Considering that the difference is very small (less than about 3.5% at most), *dTA* is very useful. It can dynamically switch between 1*TA*, 2*TA*, and 3*TA* according to the mobility pattern of a UE.

5 Conclusions

In this study, we proposed a new TAL-based paging scheme and analyzed its paging cost in LTE network. We developed a mathematical model by using 2-D random walk model and Markov chain theory to analyze the performances of previous paging schemes and our new paging scheme. Finally, we compared our paging scheme by our mathematical model with previous schemes and showed that the performance of our scheme is better than those of previous schemes in most cases. Especially, our results verified that our dynamic paging scheme, *dTA*, shows very good performance. It could dynamically switch between 1*TA*, 2*TA*, and 3*TA* according to the mobility patterns of a UE. These results can be used effectively in the design and evaluation of mobility management schemes in mobile communication networks.

Further studies are needed to improve the paging scheme assuming that any types of TA and TAL can be composed of any number of cells. An estimation algorithm is also needed in the future to properly switch between 1*TA*, 2*TA*, and so on according to the mobility pattern of a UE.

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