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Modeling and cost analysis of zone-based registration in mobile cellular networks

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This study considers zone-based registration (ZBR), which is adopted by most mobile cellular networks. In ZBR, a user equipment (UE) registers its location area (or zone) in a network database (DB) whenever it enters a new zone. Even though ZBR is implemented in most networks for a UE to keep only one zone (1ZR), it is also possible for a UE to keep multiple zones. Therefore, a ZBR with two zones (2ZR) is investigated, and some mathematical models for 2ZR are presented. With respect to ZBR with three zones (3ZR), several studies have been reported, but these employed computer simulations owing to the complexity of the cases, and there have been no reports on a mathematical 3ZR model to analyze its performance. In this study, we propose a new mathematical model for 3ZR for the first time, and analyze the performance of 3ZR using this model. The numerical results for various scenarios show that, as the UE frequently enters zones, the proposed 3ZR model outperforms 1ZR and 2ZR. Our results help determine the optimal number of zones that a UE keeps, and minimize the signaling cost for radio channels in mobile cellular networks.

KEYWORDS
location registration, mobility management, modeling, paging, performance evaluation and design, zone-based registration

1 | INTRODUCTION

In mobile cellular networks, user equipment (UE) can roam freely from place to place, and networks are required to store the location of the UE to connect incoming calls. Location registration is a process through which a UE registers its location area to a network whenever it enters a new location area, and paging is a process in which the network pages the UE to determine the exact cell in a location to which an incoming call should be connected. Because modern mobile cellular networks deal with very small cells, a high density of UEs, and high mobility, it is essential to adopt effective mobility-management schemes for location registration and paging [1,2].

Many studies have been published on various location registration schemes, and there have been studies on distance-based registration [3,4], movement-based registration [3,5–7], time-based registration, and so on [8,9]. However, most studies on mobility management have considered or included zone-based registration (ZBR) [10–16] because it is widely adopted by most mobile cellular networks. Even though ZBR is a classical approach, it shows good performance and can be easily implemented in 4G networks [17–19].

In this study, we consider zone-based registration. In ZBR, whenever a UE enters a new zone, it registers its zone to a network database (DB). Most mobile cellular networks adopt ZBR since it can be easily implemented, showing rather good performance. Even though ZBR is implemented in most networks for a UE to keep only one zone (1ZR), it is possible for a UE to keep multiple zones [10–15]. When a UE keeps multiple zones, it is expected to reduce frequent registrations through the ping-pong phenomenon around the boundary of the zones [11–15].

With respect to ZBR with multiple zones, very few studies have investigated mathematical models for ZBR with multiple zones owing to the complexity of such situations. However, even those are only for 2ZR. Lin [11] proposed a mathematical model that can analyze the performance of 2ZR. Jang and others [13] considered the implicit registration effects of outgoing calls to improve the performance of 2ZR, but this gives only a crude approximation. Baek [15] developed a simple mathematical model that is based on the Markov chain model to analyze the precise performance of 2ZR and 2ZR with implicit registration.

Then, several studies on mathematical models for 2ZR have been reported, and are compared with 1ZR from the perspective of location registration and paging costs [11–15]. However, to the best of our knowledge, there are no papers on the mathematical model of 3ZR in terms of the analysis of its performance.

In this study, we propose a new mathematical model for ZBR with three zones (3ZR) for the first time, and we present the performance of 3ZR using our model for comparison with 1ZR and 2ZR. Our proposed model is easy to understand, and can help us to determine the optimal number of zones that a UE keeps as well as to minimize the signaling cost on radio channels.

Section 2 discusses zone-based registration with three zones (3ZR). In Section 3, a new mathematical model for 3ZR is explained in detail to obtain the total signaling cost on the radio channels. Numerical results for various cases are presented in Section 4, and show that when a UE enters the zones frequently, 3ZR outperforms 1ZR and 2ZR. Finally, Section 5 concludes the paper.

2 | ZONE-BASED REGISTRATION WITH THREE ZONES

The shape of a zone is assumed to be a quadrangle, and a UE moves into one of four bordering zones.

In 3ZR, a UE can keep three zones in its ZONE_LIST. When it enters a new zone, it registers its new zone in the network databases (DBs). As a result, this new zone is inserted into the network DB, and the oldest zone is deleted from the network DB.

The UE also updates its ZONE_LIST, and this new zone is inserted into the ZONE_LIST, with the oldest zone deleted from ZONE_LIST.

However, if a UE enters the zone that is already in its ZONE_LIST, it does not register the zone in network databases, but rearranges its ZONE_LIST so as to apprehend the order of the visit. For example, let us assume that a UE enters zone I, zone J, and zone K sequentially, as shown in Figure 1.

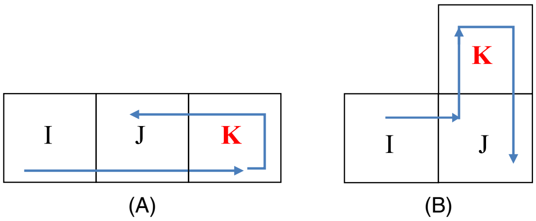


FIGURE 1 Example movements of a UE: (A) I-shaped configuration and (B) L-shaped configuration

In this case, ZONE_LIST and network DB are as follows:

$$\text{ZONE\_LIST} = [\text{I}, \text{J}, \mathbf{K}], \text{Network\_DB} = [\text{I}, \text{J}, \mathbf{K}].$$

Again, we assume that the UE in zone K moves back into zone J. In this case, the UE does not register the zone in the network DB, but it rearranges its ZONE_LIST in visiting order. As a result, ZONE_LIST and network DB are as follows:

$$\text{ZONE\_LIST} = [\text{I}, \text{K}, \mathbf{J}], \text{Network\_DB} = [\text{I}, \text{J}, \mathbf{K}].$$

Finally, we assume that in this situation, the network pages the UE to connect an incoming call to the UE. In this case, the network first pages it over zone K because the network knows that the UE is in zone K. Because the network cannot receive an acknowledgement message for the paging message, the network pages it again over the remainder of the zones, except for zone K [11–15].

For convenience, we classify three zones in 3ZR into two border zones and a center zone. In Figure 1, zone I and zone K are border zones, and zone J is a center zone. At first glance, Figure 1B appears to be different from Figure 1A, but it is sufficient to consider only Figure 1A because their stochastic characteristics are the same under the two-dimensional (2D) random walk mobility model [20].

Note that a UE registers a zone in the network DB, and that zone always becomes a border zone. Of the two border zones, we express the final registered border zone as zone R and another border zone as zone B. We also express a center zone as zone C. Then, a UE is in either of zone R, zone B, or zone C. When the network pages, if the UE is in zone R, then the first paging will be successful, and this is referred to as a zone hit; otherwise, the first paging will not be successful, which is referred to as a zone miss.

3 | PROPOSED MATHEMATICAL MODEL

In this section, we derive a mathematical model to analyze the performance of 3ZR. First, we introduce a performance measure. In this study, as in previous studies on 1ZR and 2ZR, we evaluate the total signaling cost on the radio channel, which is defined as the sum of the registration cost and paging cost.

3.1 | Location registration cost

Assume that a number of incoming calls in an hour follows a Poisson distribution with parameter λ_c, and the UE's sojourn time in a zone follows a general distribution with mean $1/\lambda_m$. It is also assumed that the probability that a UE moves back to the last zone is θ [11,13–15]. If the UE does not move to the last zone, then it moves to one of the remaining three zones with equal probability $(1 - \theta)/3$.

To analyze the location registration cost on radio channels, we need the probability that a UE enters k zones between incoming calls, $\alpha(k)$.

From the previous result, $\alpha(k)$ can be obtained as follows [11]:

$$\alpha(k) = \begin{cases} 1 - \frac{1}{\rho}\left[1 - f_m^*(\lambda_c)\right] & k = 0 \\ \frac{1}{\rho}\left[1 - f_m^*(\lambda_c)\right]^2 \left[f_m^*(\lambda_c)\right]^{k-1} & k \geq 1, \end{cases} \tag{1}$$

where $\rho = \lambda_c/\lambda_m$.

In 1ZR and 2ZR, the number of location registrations between incoming calls is given as follows [11,13–15]:

$$\begin{aligned} N_{U,1ZR} &= \frac{\lambda_m}{\lambda_c}, \\ N_{U,2ZR} &= (1-\theta)\frac{\lambda_m}{\lambda_c}. \end{aligned} \tag{2}$$

Now, let us obtain the number of location registrations between incoming calls in 3ZR. To do this, considering that a UE is in one of zone R, zone B, or zone C, we define three states of a UE in 3ZR. State R is the state in which a UE is in the last registered zone, State B is the state in which a UE is in another border zone other than the last registered zone, and State C is the state in which a UE is in the center zone.

Letting $\pi = [\pi_R\ \pi_B\ \pi_C]$ be the steady-state probability vector, π can be obtained using the following equations [21]:

$$[\pi_R\ \pi_B\ \pi_C] = [\pi_R\ \pi_B\ \pi_C]\begin{bmatrix} 1-\theta & 0 & \theta \\ 1-\theta & 0 & \theta \\ \frac{2(1-\theta)}{3} & \frac{(1+2\theta)}{3} & 0 \end{bmatrix}, \tag{3}$$

$$[\pi_R\ \pi_B\ \pi_C] \cdot \mathbf{1} = 1 \text{ where } \mathbf{1} = [1\ 1\ 1]^t.$$

Finally, the number of location registrations between incoming calls in 3ZR can be obtained as follows:

$$N_{U,3ZR} = (1-\theta)\left[\pi_R + \pi_B + \frac{2}{3}\pi_C\right]\frac{\lambda_m}{\lambda_c}. \tag{4}$$

Multiplying the number of the location registrations between incoming calls by the location registration cost U for each location registration, the location registration costs between incoming calls in 1ZR, 2ZR, and 3ZR are obtained as follows:

$$\begin{aligned} C_{U,1ZR} &= U \cdot \frac{\lambda_m}{\lambda_c}, \\ C_{U,2ZR} &= U \cdot (1-\theta)\frac{\lambda_m}{\lambda_c}, \\ C_{U,3ZR} &= U \cdot (1-\theta)[\pi_R + \pi_B + \frac{2}{3}\pi_C]\frac{\lambda_m}{\lambda_c}. \end{aligned} \tag{5}$$

3.2 | Paging cost

Now, let us analyze the paging cost between incoming calls. To connect an incoming call to the UE, the network should find the cell in which the UE is located by paging over all cells in a zone. In 1ZR, the network simultaneously pages over all cells in a zone.

Assuming that a zone is composed of n cells, the number of paged cells in 1ZR is simply as follows:

$$N_{P,1ZR} = n. \tag{6}$$

However, in 2ZR, the network first pages over one zone, and if there is no reply to the page during a predetermined time, then the network pages over another zone, which is called 2-step paging. Therefore, the number of paged cells in 2ZR is as follows [13–15]:

$$N_{P,\,2ZR} = n + n \cdot \Pr[\text{1st paging is successful}]. \tag{7}$$

With respect to 3ZR, similarly to 2ZR, we use 3-step paging. In other words, when an incoming call arrives at a UE, the network pages over zone R (the lastly registered zone), and if there is no reply to the page during a predetermined time, then the network pages over another zone. If there is still no reply to the page during the predetermined time, then the network pages over the last zone.

Therefore, the number of paged cells in 3ZR is as follows:

$$\begin{aligned} N_{P,3ZR} & \\ &= n \cdot \Pr[\text{1st paging is successful}] \\ &\quad + 2n \cdot \Pr[\text{2nd paging is successful}] \\ &\quad + 3n \cdot \Pr[\text{3rd paging is successful}] \\ &= 2n - n \cdot \Pr[\text{1st paging is successful}] \\ &\quad + n \cdot \Pr[\text{3rd paging is successful}]. \end{aligned} \tag{8}$$

Now, let us first calculate the probability that the first paging is successful. Note that paging is successful in the following two cases: (i) there are location registrations between incoming calls, (ii) there is no location registration between incoming calls.

To understand our approach, assume that ZONE_LIST = network DB = [B, C, R], which means that the UE was last registered in zone R and is still in zone R. In this case, if an incoming call to the UE arrives, the network first pages over zone R and receives an acknowledgment for the paging message (*zone hit*). Note that even though the UE last registered in zone R moves to kept zones several times, the first page will be successful if the UE moves back to zone R only when the network first pages over zone R. In other words, as shown in Figure 2, only if the UE is in its last registered zone when the network is first paged, will the first paging be successful.

Considering all possible cases, the probability that the first paging is successful is composed of the following three cases.

$$\Pr[\text{1st paging is successful}] = \omega_1 + (\pi_{\mathrm{R}} + \pi_{\mathrm{B}})\omega_2 + (\pi_{\mathrm{C}})\omega_3. \tag{9}$$

Here, we explain each case and its corresponding probability, ω_1, ω_2, and ω_3.

Case Ia. *The case in which there are registrations between incoming calls and after the last registration (the UE is in border zones), the UE does not move to other zones, or it moves to kept zones several times to be in the last registered zone when an incoming call arrives*

$$\omega_1 = \sum_{k=1}^{\infty} \omega_1(k)\alpha(k), \tag{10}$$

where

$$\omega_1(k) = (1-\theta)\sum_{i=0}^{\lfloor\frac{k-1}{2}\rfloor}\sum_{j=0}^{i}\left[\binom{i+j-1}{i-j-1} + \binom{i+j-1}{i-j}\right], \times \theta^{2i}\left[\frac{1}{3}(1-\theta)\right]^{2j}\alpha(k) \tag{11}$$

when $i + j \leq \frac{k-1}{2}$.

For example, consider the case where a UE enters six zones between incoming calls ($k = 6$). Assume that a UE receives a call in zone B and enters zone C and zone R sequentially. Assume also that when it enters zone R, it registers. If it moves to kept zones (B, C, and R) four times (in this case, $2i + 2j = 4$) to be in the last registered zone R when an incoming call arrives, then the first paging is successful. Such cases are possible when:

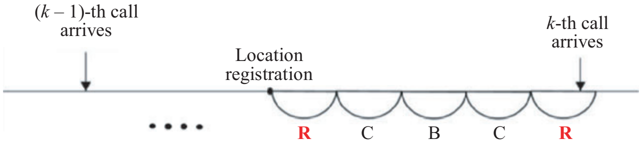
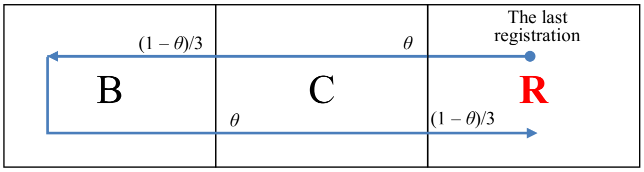
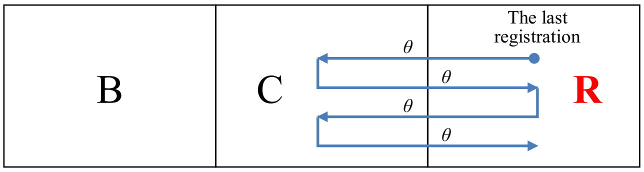


FIGURE 2 An example in which the first paging is successful



Case Ia) $i = 1, j = 1$ in (11)



Case Ia) $i = 2, j = 0$ in (11)

FIGURE 3 Examples of movements of a UE for Case Ia

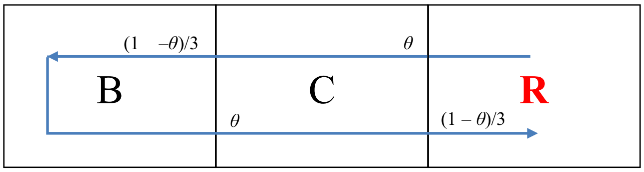
1. The UE moves to zone C→B→C→R with probability $\theta^2\left[\frac{1}{3}(1-\theta)\right]^2$ (in this case, $i = j = 1$) or
2. The UE moves to zone C→R→C→R with probability θ^4 (in this case, $i = 2$, $j = 0$), which is shown in Figure 3. Considering all possible cases such as this, we obtain the expression given in the above equations.

Case Ib. *The case in which the UE is in one of the border zones (zone R or zone B) at the last incoming call, and until the next incoming call, there is no registration, and the UE does not move to other zones or moves to only kept zones several times to be in the last called zone when the next incoming call arrives (Figure 4).*

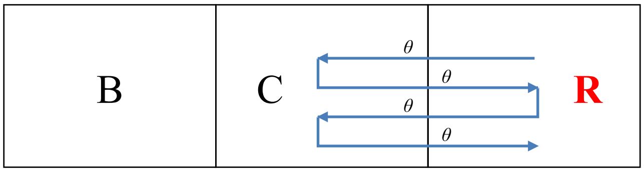
$$\omega_2 = \left\{\alpha(0) + \sum_{i=1}^{\infty}\sum_{j=0}^{i}\left[\binom{i+j-1}{i-j-1} + \binom{i+j-1}{i-j}\right] \times \theta^{2i}\left[\frac{1}{3}(1-\theta)\right]^{2j}\right\}\alpha(2i+2j). \tag{12}$$

Note that Case Ib is very similar to Case Ia, except for the condition where there is no registration.

Case Ic. *The case in which the UE is in the center zone (zone C) at the last incoming call, there is no registration until the next incoming call, and the UE does not move to other zones or moves to only kept*

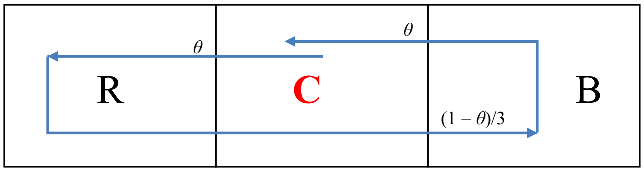


Case Ib) $i = 1, j = 1$ in (12)

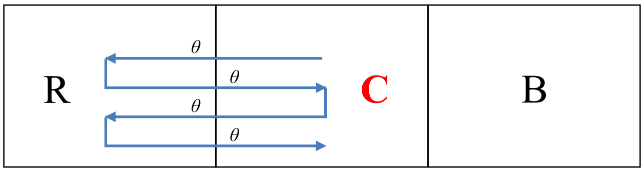


Case Ib) $i = 2, j = 0$ in (12)

FIGURE 4 Examples of movements of a UE for Case Ib

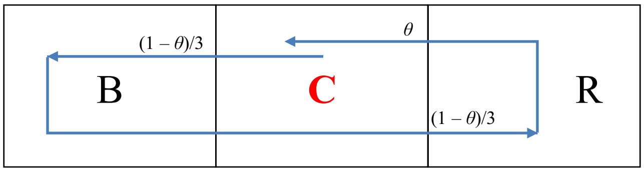


Case Ic) $i = 2, j = 1$ in (13)

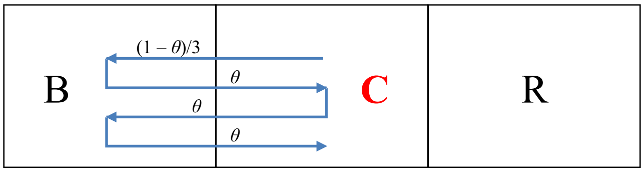


Case Ic) $i = 2, j = 0$ in (13)

(A)



Case Ic) $i = 2, j = 2$ in (13)



Case Ic) $i = 2, j = 1$ in (13)

(B)

FIGURE 5 Examples of movements of a UE for Case Ic: (A) if the left zone is the last zone (R) and (B) if the right zone is the last zone (R)

zones several times to be in the last called zone when the next incoming call arrives.

$$\omega_3=\sum_{i=0}^{\infty}\sum_{j=0}^{i}\binom{i}{j}\theta^{2i-j}\left[\frac{1}{3}(1-\theta)\right]^{j}\alpha(2i). \qquad (13)$$

For example, consider the case in which a UE enters four zones between incoming calls ($k = 4$). Assume that a UE receives a call in zone C. If it moves to kept zones (B, C, and R) four times (in this case, $2i + j = 4$) to be in the last registered zone C when an incoming call arrives, then the first paging is successful. Such cases are possible when:

1. The UE moves to zone R→C→B→C with probability $\theta^3\left[\frac{1}{3}(1-\theta)\right]+\theta^2\left[\frac{1}{3}(1-\theta)\right]^2$ or
2. The UE moves to zone R→C→R→C with probability $\theta^4+\theta^3\left[\frac{1}{3}(1-\theta)\right]$, which is shown in Figure 5. Considering all possible cases such as this, we obtain the expression given in the above equations.

In a similar way, the probability that the third paging is successful can be obtained as follows:

$$\Pr[\text{3rd paging is successful}] = \omega_4+(\pi_R+\pi_B)\omega_5+(\pi_C)\omega_6. \qquad (14)$$

We explain each case and the corresponding probability, ω_4, ω_5, and ω_6.

Case IIa. The case in which there are registrations between the incoming calls and after the last registration (the UE is in one of the border zones), the UE moves to kept zones several times to be in another border zone when an incoming call arrives.

$$\omega_4=\sum_{k=1}^{\infty}\omega_4(k)\alpha(k), \qquad (15)$$

where

$$\omega_4(k) = (1-\theta)\sum_{i=0}^{\lfloor\frac{k-3}{2}\rfloor}\sum_{j=0}^{i}\left[\binom{i+j}{i-j}+\binom{i+j}{i-j-1}\right] \times\theta^{(2j+1)}\left[\frac{1}{3}(1-\theta)\right]^{2j+1}\alpha(k), \qquad (16)$$

when $i+j\le\frac{k-3}{2}$.

Case IIb. The case in which the UE is in one of the border zones (zone R or zone B) at the last incoming call, there is no registration until the next incoming call, and the UE moves to only kept zones several times to be in another border zone when the next incoming call arrives.

$$\omega_5=\sum_{i=0}^{\infty}\sum_{j=0}^{i}\left[\binom{i+j}{i-j}+\binom{i+j}{i-j-1}\right] \times\theta^{2i+1}\left[\frac{1}{3}(1-\theta)\right]^{2j+1}\alpha(2i+2j+2). \qquad (17)$$

Case IIc. The case in which the UE is in the center zone (zone C) at the last incoming call, there is no registration until the next incoming call, and the

UE moves to only kept zones several times to be in one of border zones (zone R or zone B) when the next incoming call arrives.

$$\omega_6 = \sum_{i=0}^{\infty}\sum_{j=0}^{i}\binom{i}{j}\theta^{2i-j}\left[\frac{1}{3}(1-\theta)\right]^{j+1}\alpha(2i+1). \quad (18)$$

Assuming that the paging cost for one cell is P, the paging cost of each scheme, C_P, can be obtained as follows:

$$\begin{aligned} C_{\mathrm{P,1ZR}} &= n\cdot P,\\ C_{\mathrm{P,2ZR}} &= P\cdot(n + n\cdot \Pr[\text{2nd paging is successful}]),\\ C_{\mathrm{P,3ZR}} &= P\cdot(2n - n\cdot \Pr[\text{1st paging is successful}]\\ &\qquad + n\cdot \Pr[\text{3rd paging is successful}]). \end{aligned} \quad (19)$$

3.3 | Total cost

The total signaling cost on the radio channels is the sum of the registration cost and paging cost.

$$\begin{aligned} &C_{\mathrm{T,3ZR}}\\ &\quad = C_{\mathrm{U,3ZR}} + C_{\mathrm{P,3ZR}}\\ &\quad = U\cdot(1-\theta)\left[\pi_{\mathrm{R}} + \pi_{\mathrm{B}} + \frac{2}{3}\pi_{\mathrm{C}}\right]\frac{\lambda_{\mathrm{m}}}{\lambda_{\mathrm{c}}} \\ &\qquad + P\cdot(2n - n\cdot \Pr[\text{1st paging is successful}]\\ &\qquad + n\cdot \Pr[\text{3rd paging is successful}]). \end{aligned} \quad (20)$$

4 | NUMERICAL RESULTS

In this section, using our mathematical model in Section 3, we compare the performance of 1ZR, 2ZR, and 3ZR. The following are assumed [11–16]:

1. The network is composed of square zones of the same size. Therefore, a UE moves into one of four bordering zones.
2. A UE receives λ_c calls in an hour ($\lambda_c = 1$).
3. A UE enters λ_m zones in an hour ($\lambda_m = 1$).
4. The probability that a UE moves back to the last zone, θ, is 0.3.

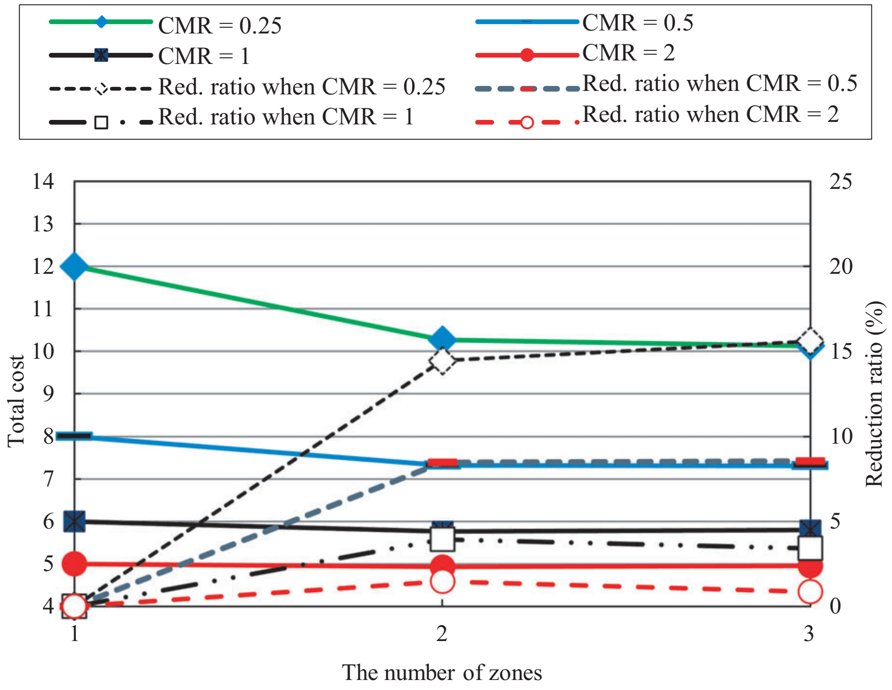


FIGURE 6 Total costs for various numbers of zones

TABLE 1 Total costs for various numbers of zones (*: minimum)

ZBR schemes	1ZR	2ZR	3ZR	(1ZR−2ZR)/1ZR	(1ZR−3ZR)/1ZR
Total cost when CMR = 2	5	**4.9264***	4.9568	**1.47%**	0.86%
Total cost when CMR = 1	6	**5.7636***	5.7953	**3.94%**	3.41%
Total cost when CMR = 0.5	8	7.3217	**7.3155***	8.48%	**8.56%**
Total cost when CMR = 0.25	12	10.2667	**10.1288***	14.44%	**15.59%**

5. The location registration cost for each location registration, U, is 4 [14].
6. The paging cost for one cell, P, is 1.

In this section, the UE's sojourn time in a zone is assumed to follow an exponential distribution with mean $1/\lambda_m$, for computational conveniences. Note that it is possible to assume that the UE's sojourn time in a zone follows a general distribution.

4.1 | Total costs for various numbers of zones

Figure 6 and Table 1 show the total costs of 1ZR, 2ZR, and 3ZR for various call-to-mobility (CMR = λ_c/λ_m) ratios. CMR = 1/2 indicates that the UE enters two zones between incoming calls. Note that fewer CMR means that the UE enters more zones between incoming calls.

Based on the above, we can see that when CMR = 0.25, the total cost of 2ZR is less than that of 1ZR by 14.44%, and the total cost of 3ZR is less than that of 1ZR by 15.59%. In general, the smaller the value of CMR, the better is the relative performance of 3ZR. According to the many numerical results for various circumstances, when CMR is greater than or equal to 1, the optimal number of zones that minimizes the total signaling cost is two in most cases. However, when CMR is very small, for example, 0.5 or less, the optimal number of zones is three.

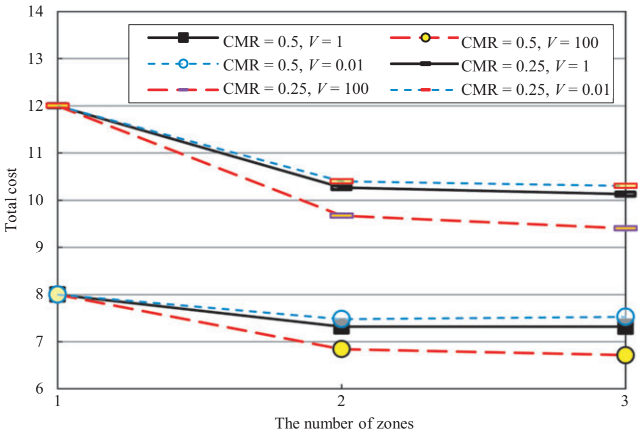


FIGURE 7 Total costs for various gamma distributions

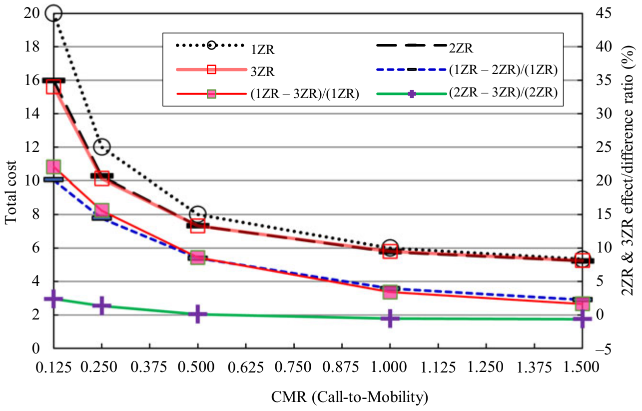


FIGURE 8 Total costs for various CMRs (n = 4)

Figure 7 shows the total costs of 1ZR, 2ZR, and 3ZR when the UE's sojourn time in a zone follows various gamma distributions for CMR = 0.25 and 0.5. In the figure, we can see that as the variance (V) increases, the less is the total cost. As a result, when the UE's sojourn time follows a gamma distribution with a very large variance (eg, V = 100), the optimal number of zones is more likely to be three for very small CMR (eg, CMR = 0.5 or less).

4.2 | Total cost for various CMRs

Figure 8 and Table 2 show the total cost for various CMR ratios. In order to consider real situations, the CMR value is considered to range from 0.125 to 2.00. When a CMR is low (eg, when CMR = 0.125), 3ZR outperforms 2ZR. However, when CMR is high (eg, when CMR = 2.00), 2ZR outperforms 3ZR. Note that as CMR increases, the relative gap between 1ZR and 2ZR/3ZR decreases, and 1ZR is expected to outperform 2ZR/3ZR when CMR is very high (eg, when CMR = 3 or 4). According to previous studies on 2ZR [11,13–15], 1ZR may outperform 2ZR when CMR is very high.

In summary, even though there may be a difference with regard to which one of 1ZR, 2ZR, or 3ZR outperforms other schemes according to the λ_c/λ_m ratio, it should be noted that 3ZR may outperform 1ZR/2ZR as CMR becomes low.

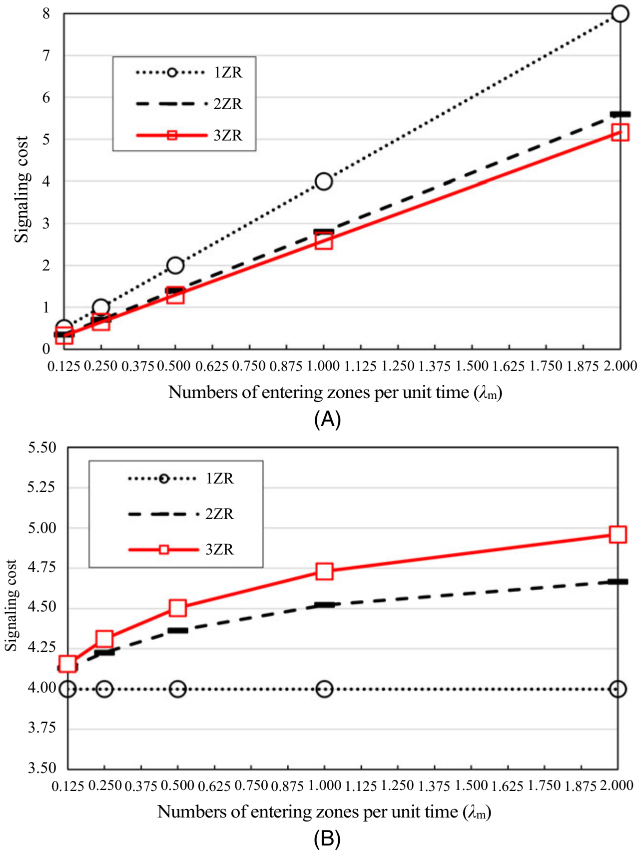
4.3 | Registration cost and paging cost for various numbers of entering zones per unit time

As previously described, the total cost is defined as the sum of the registration cost and paging cost. In 3ZR, compared to 1ZR/2ZR, the registration cost is expected to decrease and the paging cost to increase.

Figure 9 shows the registration cost and paging cost for various numbers of entering zones per unit time, λ_m. From the figure, as UE frequently enters zones, the registration costs of all three ZBR schemes increases, but the speed of increase for each scheme is different. As the UE frequently enters zones, the registration cost for 1ZR increases drastically, but that of 3ZR increases slowly compared to 1ZR/2ZR. Furthermore, as the UE enters zones frequently, while

TABLE 2 Total costs for various CMRs ($n = 4$, *: minimum)

CMR	0.125	0.250	0.500	1.000	1.500
TC (1ZR)	20	12	8	6	5
TC (2ZR)	15.9742	10.2667	7.3217	**5.7636***	**4.9264***
TC (3ZR)	**15.5920***	**10.1288***	**7.3155***	5.7653	4.9568
{(1ZR − 2ZR)/1ZR} × 100	20.13%	14.44%	8.48%	**3.94%**	**2.27%**
{(1ZR − 3ZR)/1ZR} × 100	**22.04%**	**15.59%**	**8.56%**	3.41%	1.65%
{(2ZR − 3ZR)/2ZR} × 100	2.39%	1.34%	0.0%	−0.55%	−0.64%



(A)

(B)

FIGURE 9 Registration cost and paging cost for various numbers of entering cells: (A) registration cost for various λ_m and (B) paging cost for various λ_m

the registration cost of 1ZR is constant and that of 2ZR increases slightly, the cost of 3ZR decreases significantly.

As a result, 3ZR is expected to outperform 1ZR/2ZR when the UE frequently enters zones.

4.4 | Total cost for various values of θ

Figure 10 shows the total cost for various probabilities of moving back to the last zone, θ. As shown in the figure, the total cost of 2ZR and 3ZR decreases as θ increases. Note that the total cost of 3ZR decreases more than that of 2ZR in the above environment. Even if it is apparent that the total costs of 2ZR and 3ZR decrease as θ increases, it appears unrealistic to assume that θ is larger than 0.5 in real mobile cellular networks.

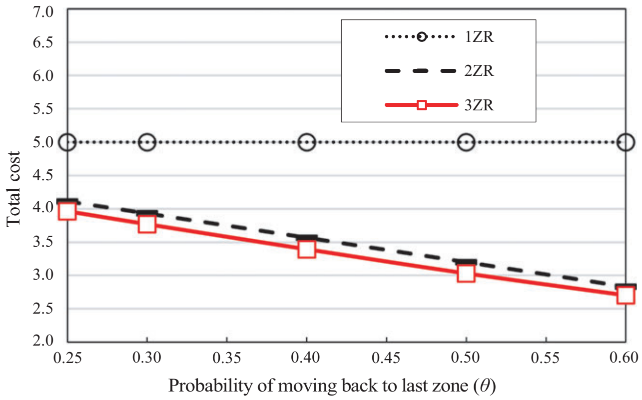


FIGURE 10 Total cost for various θ

5 | CONCLUSION

This study considered zone-based registration, which has been adopted by most mobile cellular networks. Even though in most networks, ZBR is implemented in order for a UE to keep only one zone, it is possible for a UE to keep multiple zones. In particular, we proposed a new mathematical model for ZBR with three zones (3ZR) for the first time, and analyzed the performance of 3ZR using the proposed model. Because no hardware modifications are required to implement 3ZR, it can be easily implemented by modifying 4G networks as well as existing 1ZR-based networks.

The numerical results for various situations show that when a UE enters zones more frequently than to receive calls (in other words, CMR is small), 3ZR outperforms 1ZR and 2ZR. By considering that 2ZR outperforms 3ZR in some conditions, we will investigate an adaptive scheme to dynamically switch between 2ZR and 3ZR according to the CMR ratio. Our future research includes modeling for ZBR with N zones ($N \geq 4$), and finding the optimal number of zones to minimize the signaling costs on radio channels.

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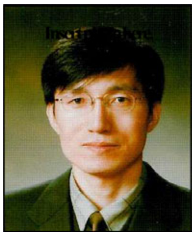

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