On the Design of Delay based Admission Control in Hierarchical Cellular Networks

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Abstract

Today, as the hierarchical cellular system is getting more attention than before, some recent studies introduce delay based admission control (AC) scheme which delays the admission to the macro-embedded small cell for a relatively short time to prevent unnecessary handover caused by the short-term visitors of the small cell area. In such delay based ACs, when we use improper delay parameter, the system frequently makes incorrect handover decisions such as where unnecessary handover is allowed due to too short delaying, or where necessary handover is denied due to too long delaying. In order to avoid these undesirable situations as much as possible, we develop a new delay parameter decision method based on probabilistic cell residence time approximations. By the extensive numerical and analytical evaluations, we derive two useful design insights for determining the proper delay parameter which prevents the incorrect handover decision as much as possible. We expect our delay parameter decision method and design insights can be useful system administration tips in hierarchical cellular system where delay based AC is adopted.

Keywords: hierarchical cellular networks, reducing unnecessary handover, delay based admission control, performance metric, protocol design

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1. Introduction

Hierarchical cellular network is a type of cellular network where a macro cell includes many macro-embedded small cells such as mirco, femto cells or Wi-Fi hotspots [1][2][3]. Exploiting the low deployment and administration costs of small cells, the hierarchical cellular network provides enhanced spatial capacity compared to conventional macro cell only system with relatively low costs. However, in hierarchical network, as the number of macro-embedded small cell increases, the macro base stations has to bear large burdens to process so many inter-tier handovers as illustrated in **Fig. 1**. Hence, reducing *unnecessary handover* is one of the important matters in hierarchical multi-tier systems [4][5].

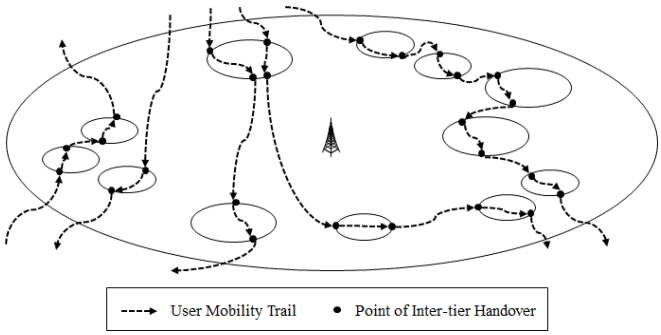


Fig. 1. Frequent inter-tier handovers in hierarchical cellular networks

Conventionally, the term *unnecessary handover* refers to *ping-pong effect* which means that the mobile station continues to be handed back and forth between two base stations at cell boundary area [6]. In hierarchical cellular network, however, it is desirable to make the term *unnecessary handover* have broader definition. According to the measurement from the wireless test-bed in *Carnegie Mellon* University [7], around 50% and 70% of mobile users stay in small cells[1] for less than 3 and 10 seconds respectively. From this, *unnecessary handover* need to include not only the *ping-pong effect*, but also the handovers caused by short-term residence users who stay in a small cell for less than given time discriminant decided by network administrator. Thereby, if we prevent such a short-term residence user from being handed to the small cell, the number of *unnecessary handover* will be significantly reduced.

To filter out the handover of short-term residence user, recent studies introduce delay based admission control (AC) for macro → small cell handover decision [8][9][10][11][12]. In the delay based AC, when the user comes into the small cell area, the system does not start the handover process immediately. Rather, the system suspends the handover until pre-determined delay time goes by. If the user is still within the small area after delay time, the system eventually starts handover process. Conversely, if the mobile user comes back out of the small cell before the delay time elapses, the macro → small cell handover is automatically avoided. By this mechanism, delay based AC suppresses the occurrence of *unnecessary handovers* made by short-term residence users. The delay based AC is simple, but efficient enough to prevent unnecessary handovers of short-term visitors like who quickly passes by the edge of the small cell area.

[1] At that time, 650 stations are deployed on 300,000 square-feet areas. The mean communication range of each station is about 12m.

However, there are still an important problematic issue about delay parameter decisions. If we use too short delay parameter, the protocol may improperly allow unnecessary handovers made by short-term residence users. On the other hands, if we use too long delay parameter, the system prevent not only unnecessary handover, but also unnecessary handover made by long-term enough residence user. Hence, we need to choose the delay parameter such that the possibility of above incorrect decision is minimized.

By observing the cases of incorrect handover decisions in delay based AC, we discover that the occurrence of incorrect handover decision can be checked by the relationships among the user's cell residence time t_R, short-residence time discriminant t_{Th}, and the delay parameter d. Based on the observations, we make a new performance metric called as *incorrect handover decision probability* which quantifies the possibility of incorrect handover decision. From this, we can represent the proper delay parameter decision problem as the optimization problem which chooses the delay parameter d that minimizes the incorrect handover decision probability.

By using extensive numerical evaluations, we observe how of t_R, t_{Th}, and d affect the incorrect handover decision probability. From the numerical results, we derive useful design insights about determining the proper delay parameter. Our delay parameter decision method make the delay based AC significantly reduce the number of macro → small cell handover with relatively low incorrect handover decision probability.

To the best of our knowledge, our work is first research about the delay parameter decision steps in delay based AC. Existing works consider only the handover decision or processing steps assuming the proper delay parameter is already given [8][9][10][11][12]. We expect our work is useful reference to the network administrator who operates hierarchical cellular network where delay based AC is adopted for macro → small cell handover.

The remaining part of this paper is as followings: In section 2, we explain delay based AC from the protocol perspective. Delay parameter design problem is discussed in section 3. Then, numerical evaluations are presented in section 4. In section 5, we present two useful design insights about delay parameter decision problem. Finally, we conclude in section 6.

2. Delay based Admission Control

As described in section 1, delay based AC refers to delaying macro → small cell handover for pre-determined delay time when the mobile user comes into the small cell area. Actually, whether the mobile user is within the small cell area is determined by checking SINR (Signal-to-Interference-and-Noise-Ratio) of the small cell base station. Thus, delay based AC is implemented by modifying the SINR scanning and handover decision procedure of conventional AC protocol. Detailed procedures are as followings:

Step 1: If the mobile device is approaching to the base station of small cell *S*, it detects the signals of *S* by periodical signal scanning. (The scanning interval is varied from few tens of milliseconds to few tens of seconds [13].) Here, the system checks if the following condition is satisfied:

$$S_S > \alpha \cdot S_M + (1-\alpha) \cdot S_S + \Delta \tag{2.1}$$

where S_M is the SINR of currently connected macro cell, S_S is the SINR of the target small cell, α ($0 \le \alpha \le 1$) is scaling factor, and Δ is the hysteresis to prevent ping-pong effect. Eq. (2.1) is the SINR condition for macro → small cell handover proposed by *Moon et. al* [14]. Of course, it is no matter to use another type of criterion according to administration policy. For example,

we can change eq. (2.1) to the handover criterions proposed by [15] [16] [17] which are designed to enhance the various system performance.

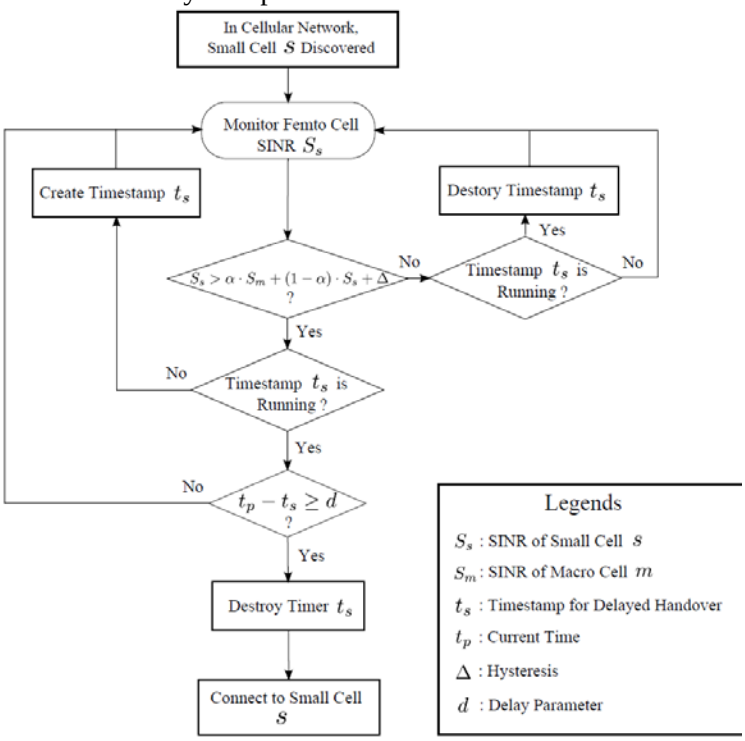


Fig. 2. The flow chart of delay based AC

Step 2: When eq. (2.1) is satisfied, the system assumes that the mobile user comes into the small cell area. However, the system does not start macro → small cell handover immediately. Instead, the system makes the reservation for the handover after waiting for d. It generates the timestamp t_S which is used for checking the cell residence time of the mobile user.

Step 3: After the reservation, whenever the scanning period returns, the system checks if eq. (2.1) is still satisfied. If it is, the system proceeds to step 5 as next procedure. Otherwise, the system proceeds to step 4.

Step 4: In this case, the system assumes that the mobile user comes back out of the small cell. And then, it destroys t_S to cancel the reservation for macro → small cell handover. By this mechanism, unnecessary handover of short-term residence user is automatically avoided.

Step 5: In this case, the system assumes that the mobile user still stays in the small cell area. Then, it calculates the difference of the present time t_P and timestamp t_S. If the difference is smaller than d, the system turns back to step 3. Otherwise, the system eventually starts macro → small cell handover. At this moment, $|t_P - t_S| \geq d$ means that the delay time elapses.

3. Delay Parameter Design Problem

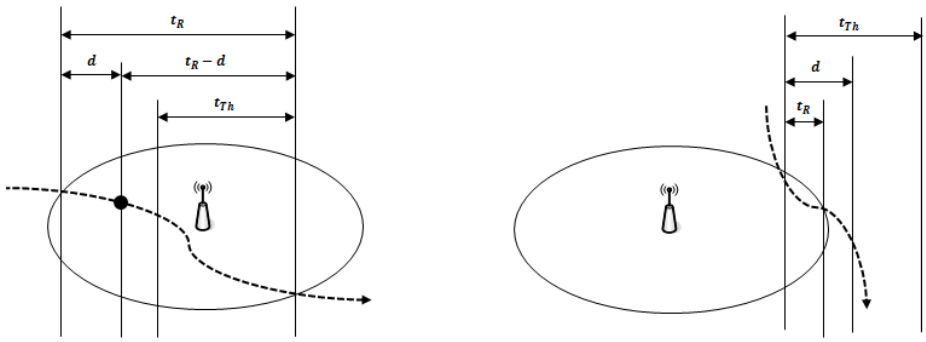
3.1 Decision Correctness of Delay based AC

The goal of delay based AC is preventing unnecessary handovers made by short-term residence users. However, as discussed earlier, improper delay parameter may cause the delay based AC makes incorrect handover decision such as denying of necessary handover, or

allowance of unnecessary handover. To formulate the decision correctness of delay based AC, we define a decision verifier function $v(t_R, t_{Th}, d)$ as following:

$$\mathrm{v}(t_R, t_{Th}, d) = \begin{cases} 1, & \textbf{case 1}: \textit{when handover occurs, and } t_R - d \geq t_{Th} \\ 1, & \textbf{case 2}: \textit{when handover does not occur, and } t_R < t_{Th} \\ 0, & \textbf{case 3}: \textit{all other situations except for the case } 1 \textit{ and } 2 \end{cases} . \quad (3.1)$$

In the eq. (3.1), case 1 means the proper allowance of necessary handover as illustrated in **Fig. 3 (a)**. Here, one notable thing is that we use $t_R - d \geq t_{Th}$ instead of $t_R \geq t_{Th}$ as a criterion of proper handover allowance. This is because, in delay based AC, the effective access time to the small cell is $t_R - d$ due to delaying before the actual macro → small cell handover. And, case 2 means the proper prevention of unnecessary handover as illustrated in **Fig. 3 (b)**. Case 3 means all improper situations which do not satisfy the conditions of case 1 or 2.



(a) Handover occurs thanks to $t_R \geq d$ (b) Handover does not occurs due to $t_R < d$

Fig. 3. The examples of correct decision of delay based AC

3.2 Determining the Proper Delay Parameter

Considering the goal of the delay based AC, eq. (3.1) is an essential component to determine the proper delay parameter d. In other words, it is desirable to determine d such that the system avoids the situation where $v(t_R, t_{Th}, d)$ =0 as much as possible. For easier understanding, let us look at an example where a system uses delay based AC and t_{Th} is 3 seconds. If a mobile user comes and stays in the small cell for 7 seconds, we need to set $d \leq 4$ to make $v(7, 3, d)$=1.

If the system knows exactly in advance t_R of the incoming mobile user to the small cells, we will always makes $v(t_R, t_{Th}, d)$=1. However, unfortunately, it is impossible because the cell residence time of each user which is undeterministic. Therefore, the most practical approach is to set d as a constant that minimizes the probability of $v(t_R, t_{Th}, d)$=0 for given t_{Th} and t_R. Since t_R is undeterministic, it can be expressed as a random variable. Hence, determining the proper delay parameter of delay based AC can be following minimization problem:

$$\arg min_d Pr[v(t_R, t_{Th}, d) = 0] \quad (3.2)$$

where t_{Th} is given by network administrator, and t_R is a random variable which follows an arbitrary probability distribution. The probability distribution function of t_R can be obtained by approximating the statistics about the user residence time collected by base stations. And from now on, we refer $Pr[v(t_R, t_{Th}, d) = 0]$ to *incorrect handover decision probability*.

The next thing we have to do is to discover how we calculate incorrect handover decision probability. According to our observation, whether $v(t_R, t_{Th}, d) = 0$ or not is determined by the relationships among t_R, t_{Th}, and d. There are 8 distinct size relationships made from (t_R,

t_{Th}, d)-tuples. For each case, we study when $v(t_R, t_{Th}, d) = 0$. We list the situational analysis for each case as followings:

Case 1 ($\boldsymbol{t_R < d \le t_{Th} < d + t_{Th}}$): Handover does not occur due to $t_R < d$. And, $v(t_R, t_{Th}, d) = 1$ thanks to $t_R < t_{Th}$. In this case, the delay based AC properly prevents unnecessary handover caused by short-term residence user.

Case 2 ($\boldsymbol{d < t_R < t_{Th} < d + t_{Th}}$): Handover occurs due to $t_R > d$. However, since $t_R < d + t_{Th}$ ($\Leftrightarrow t_R - d < t_{Th}$), $v(t_R, t_{Th}, d) = 0$. This case means the mobile user handed to the small cell becomes short-term residence user because of improper delaying.

Case 3 ($\boldsymbol{d \le t_{Th} \le t_R < d + t_{Th}}$): Handover occurs due to $t_R \ge d$. However, the same reason as in the case 2, $v(t_R, t_{Th}, d) = 0$. Same as the case 2, this case also means the mobile user handed to the small cell becomes short-term residence user because of improper delaying.

Case 4 ($\boldsymbol{d \le t_{Th} < d + t_{Th} < t_R}$): Handover occurs due to $t_R > d$. And, $v(t_R, t_{Th}, d) = 1$, thanks to $t_R > d + t_{Th}$ ($\Leftrightarrow t_R - d > t_{Th}$). In this case, the delay based AC properly allows necessary handover made by enough-residence time user.

Case 5 ($\boldsymbol{t_R < t_{Th} < d < d + t_{Th}}$): Handover does not occur due to $t_R < d$. And, $v(t_R, t_{Th}, d) = 1$ due to $t_R < t_{Th}$. In this case, same as in the case 1, the delay based AC properly prevents unnecessary handover caused by short-term residence user.

Case 6 ($\boldsymbol{t_{Th} \le t_R < d < d + t_{Th}}$): Handover does not occur due to $t_R < d$. However, $v(t_R, t_{Th}, d) = 0$ thanks to $t_R > t_{Th}$. This case means that the necessary handover is incorrectly suppressed due to delay based AC.

Case 7 ($\boldsymbol{t_{Th} < d \le t_R < d + t_{Th}}$): Handover occurs due to $t_R \ge d$. However, since $t_R < d + t_{Th}$ ($\Leftrightarrow t_R - d < t_{Th}$), $v(t_R, t_{Th}, d) = 0$. Same as the case 2 and 3, this case means the mobile user handed to the small cell becomes a short-term residence user because of improper delaying.

Case 8 ($\boldsymbol{t_{Th} < d < d + t_{Th} \le t_R}$): Handover occurs due to $t_R > d$. And, $v(t_R, t_{Th}, d) = 1$, due to $t_R \ge d + t_{Th}$ ($\Leftrightarrow t_R - d \ge t_{Th}$). In this case, necessary handover is properly admitted.

Among above 8 cases, when the delay based AC makes incorrect decision are the case 2, 3, 6, and 7. When we have the probability distribution of t_R, we can obtain the incorrect handover decision probability by summing the probabilities of these cases. Hence, the incorrect handover decision probability is as

$$
\begin{aligned}
&Pr[v(t_R, t_{Th}, d) = 0] \\
&= \begin{cases} \Pr[case\ 2] + \Pr[case\ 3], & d \le t_{Th} \\ \Pr[case\ 6] + \Pr[case\ 7], & d > t_{Th} \end{cases} \\
&= \begin{cases} \Pr[d \le t_R < t_{Th} < d + t_{Th}] + \Pr[d \le t_{Th} < t_R < d + t_{Th}], & d \le t_{Th} \\ \Pr[t_{Th} \le t_R < d < d + t_{Th}] + \Pr[t_{Th} < d \le t_R < d + t_{Th}], & d > t_{Th} \end{cases} \\
&= \begin{cases} \Pr[d \le t_R < d + t_{Th}], & d \le t_{Th} \\ \Pr[t_{Th} \le t_R < d + t_{Th}], & d > t_{Th} \end{cases} \\
&= \begin{cases} \int_d^{d+t_{Th}} f_{t_R}(t)dt, & d \le t_{Th} \\ \int_{t_{Th}}^{d+t_{Th}} f_{t_R}(t)dt, & d > t_{Th} \end{cases}.
\end{aligned} \tag{3.3}
$$

It is obvious that the incorrect handover decision probability is directly derived by the pdf (probability density function) or cdf (cumulative distribution function) of t_R. Thus, when t_{Th} is given from network administrator, the minimization problem (3.2) is solved by using the pdf or cdf of t_R.

By observing the eq. (3.2) and (3.3), we find a useful property: the solution of (3.2) is not higher than t_{Th}. We represent this as following theorem.

Theorem 1 For an arbitrary pdf of t_R, the solution of the eq. (3.2) cannot be higher than t_{Th}.

***Proof*:** This can be proved by showing that the $Pr[v(t_R, t_{Th}, t_{Th}) = 0]$ always smaller than $Pr[v(t_R, t_{Th}, t_{Th} + \delta) = 0]$ $(0 < \delta < \infty)$. First, when $d = t_{Th}$, eq. (3.3) is

$$Pr[v(t_R, t_{Th}, t_{Th}) = 0] = \int_{t_{Th}}^{2t_{Th}} f_{t_R}(t)dt. \tag{3.4}$$

And, when $d > t_{Th}$, d can be represented as $t_{Th} + \delta$. Eq. (3.3) is

$$Pr[v(t_R, t_{Th}, t_{Th} + \delta) = 0] = \int_{t_{Th}}^{2t_{Th}+\delta} f_{t_R}(t)dt. \tag{3.5}$$

For the property of the integration, equation (3.4) is always smaller than (3.5). This means that the solution of eq. (3.2) must not be higher than t_{Th}. ■

Theorem 1 shows we do not have to consider the case $d > t_{Th}$ any more when we determine the proper delay parameter. Now, eq. (3.2) can be simplified as

$$\arg min_d Pr[v(t_R, t_{Th}, d) = 0] = \int_d^{d+t_{Th}} f_{t_R}(t)dt, (d \le t_{Th}) \tag{3.6}$$

Eq. (3.6) can be solved by the numerical minimization technique when the constant t_{Th} and the random variable t_R are given [7].[2]

4. Numerical Evaluations

In this section, we perform numerical experiments to look at the effects of t_{Th} and d on the incorrect handover decision probability in order to obtain the design insights for the proper delay parameter decision. *Khan et. al* study various probability distribution functions which can be used to describe the cell residence time of mobile users [18]. By using those functions as the pdf of t_R, we measure how incorrect handover decision probability and handover reduction ratio changes with respect to t_{Th} and d. The handover reduction ratio R_h is the ratio of users whose residence time is less than d to the total mobile users. This can be expressed as

$$R_h = \Pr[t_R < d] = 1 - \int_d^{\infty} f_{t_R}(t)dt = \int_0^d f_{t_R}(t)dt. \tag{4.1}$$

The table 1 lists the types and their pdfs which specify t_R in our experiments. Among the distributions in [7], we omit *Erlang* and *Uniform* distributions in our experiments. This is because (a) we already use *Gamma* distribution which is the generalization of Erlang distribution and (b) *Uniform* distribution is not realistic [19].

Table 1. The probability distributions used for experiments

Name	Notation	PDF (Probability Distribution Function)
Exponential	$t_R \sim Exp(\eta)$	$\eta e^{-\eta t}$
Gamma	$t_R \sim \Gamma(\alpha, \beta)$	$\frac{\beta^{\alpha} \cdot t^{\alpha-1} \cdot e^{-\beta t}}{\Gamma(\alpha)}$ where $\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt$
Weibull	$t_R \sim \mathrm{WEB}(\alpha, \beta)$	$\frac{\beta t^{\beta-1}}{\alpha^{\beta}} e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$
***Pareto* (Type I)**	$t_R \sim \mathrm{P(I)}(\alpha, t_{min})$	$\alpha \cdot \frac{t_{min}{}^{\alpha}}{t^{\alpha \mp 1}}, (t \ge t_{min})$

[2] Even if $f_{t_R}(t)$ is complicated form and so difficult to apply well-known minimization technique, we can obtain practical approximate solution by exhaustive searching with limited accuracy of d such as few milliseconds.

To make t_R have short-term residence property, we decide the parameters of each distribution in the table 1 such that (a) median is 3 seconds, and (b) 50 ~ 55% of the random variable is less than median. These characteristics are based on the measurement data in [7] which studies the cell residence time of mobile users in small-scale cellular networks. The input distributions of t_R in our experiments are as followings:

***Exponential* Distribution ($t_R \sim Exp(0.2634)$):** $0.2634e^{-0.2634t}$ (4.2)

***Gamma* Distribution ($t_R \sim \Gamma(3.5, 1.1275)$):** $0.4580 \cdot t^{2.5} \cdot e^{-1.1275t}$ (4.3)

***Weibull* Distribution ($t_R \sim \mathrm{WEB}(3.8, 0.9965)$):** $0.2635 \cdot t^{-0.035} \cdot e^{-\left(\frac{t}{3.8}\right)^{0.9965}}$ (4.4)

***Pareto* Distribution ($t_R \sim \mathrm{P(I)}(0.183, 0.06)$)** [3]**:** $0.1094t^{-1.183}$ (4.5)

Using the equations (4.2) - (4.5) as inputs, we measure the incorrect handover decision probabilities and handover reduction ratios.

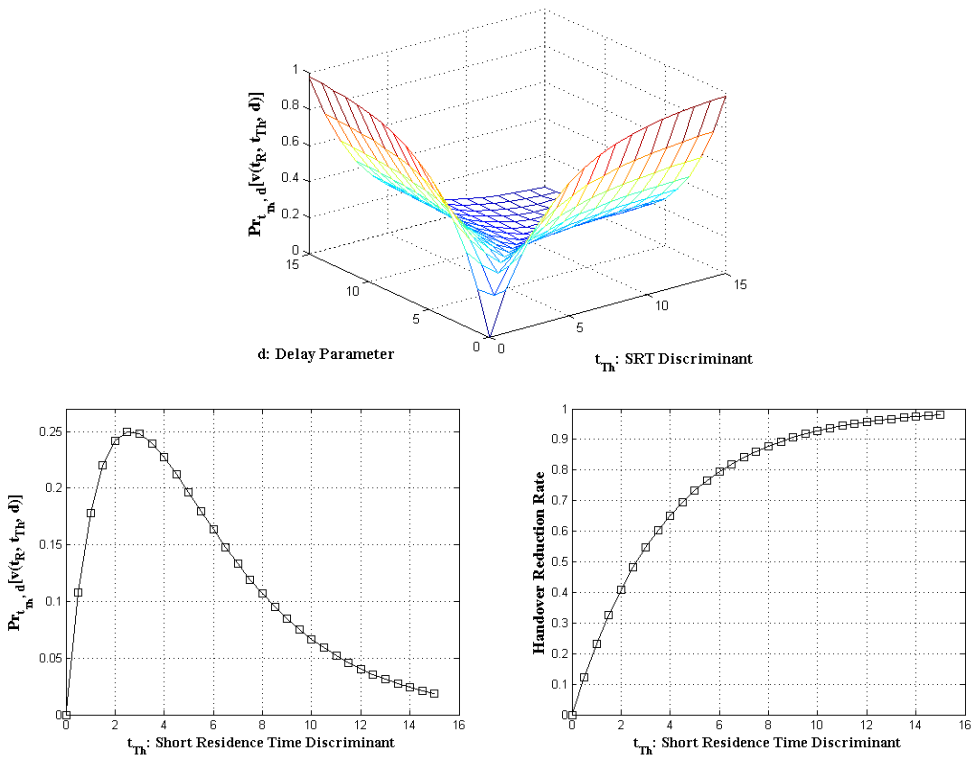


Fig. 4. The numerical results for $t_R \sim Exp(0.2634)$: (a) incorrect handover decision probability according to t_{Th} and d (b) incorrect handover decision probability according to t_{Th} (c) handover reduction probability according to t_{Th}

Fig. 4 shows the numerical results of *Exponential* distribution for eq. (4.2). **Fig. 4 (a)** shows how the incorrect handover decision probability changes according to t_{Th} and d. In this figure, we can see that the incorrect handover decision probability is smaller when $t_{Th} = d$ than when $t_{Th} \neq d$. In short, the optimal delay parameter is t_{Th}. In fact, this property holds when

[3] We set t_{min} as 0.06 seconds because current IMT-Advanced specification [20] defines the maximum handover processing time as 0.06 seconds.

the pdf of t_R is monotonic decreasing function. We present generalized theorem about it later. **Fig. 4 (b)** shows the incorrect handover decision probability according to t_{Th} where d is the solution of eq. (3.6). Since the optimal solution of (3.6) is equivalent to t_{Th} in this case, the figure shows the values of $Pr_{t_{Th},d}[v(t_R, t_{Th}, t_{Th}) = 0]$. The plot increases until at around 2.6 seconds, and then decreases thereafter. The highest incorrect handover decision probability is around 25% when t_{Th} is at around 2.6 seconds. **Fig. 4 (c)** plots the handover reduction rate according to t_{Th}. Same as the **Fig. 4 (b)**, this result is also about where $d = t_{Th}$. As t_{Th} increases, the amount of handover avoidance also increases. Due to $R_h = \Pr[t_R < d]$, the increasing pattern of the handover reduction rate is same as the cdf of t_R.

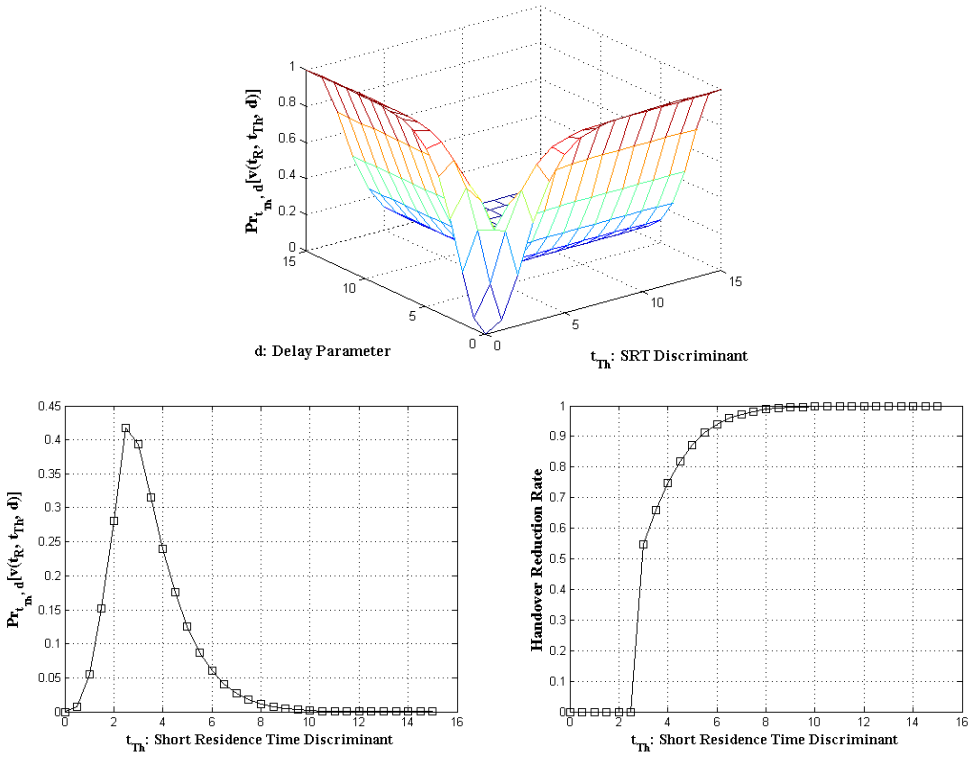


Fig. 5. The numerical results for $t_R \sim \Gamma(3.5, 1.1275)$: (a) incorrect handover decision probability according to t_{Th} and d (b) incorrect handover decision probability according to t_{Th} (c) handover reduction probability according to t_{Th}

Fig. 5 shows the numerical results of the *Gamma* distribution for eq. (4.3). **Fig. 5 (a)** shows how the incorrect handover decision probability changes according to t_{Th} and d. In the figure, we can see that the proper delay parameter is different upon the value of t_{Th}. When t_{Th} is within the range where the pdf of t_R increases, the incorrect handover decision probability is decreased as d decreases. Namely, the incorrect handover decision probability is minimized when $d = 0$. On the other hands, when t_{Th} is within the range where the pdf of t_R decreases, the solution of the equation (3.6) is t_{Th}. This is same as in the case of *Exponential* distributions. **Fig. 5 (b)** shows incorrect handover decision probability according to t_{Th} where d is the solution of eq. (3.6). Thus, in this plot, when t_{Th} is less than around 2.2, $d = 0$, and when thereafter, $d = t_{Th}$. The changing pattern is similar to, but little more drastic than, that of

exponential distributions. The highest incorrect handover decision probability is at around 40%. **Fig. 5 (c)** plots the handover reduction rate where d is the solution of eq. (3.6). In this figure, when t_{Th} is less than around 2.2, the reduction rate is 0 because of the solution of the equation (3.6) is 0. After that point, the handover reduction rate increases in same pattern as the cdf of t_R.

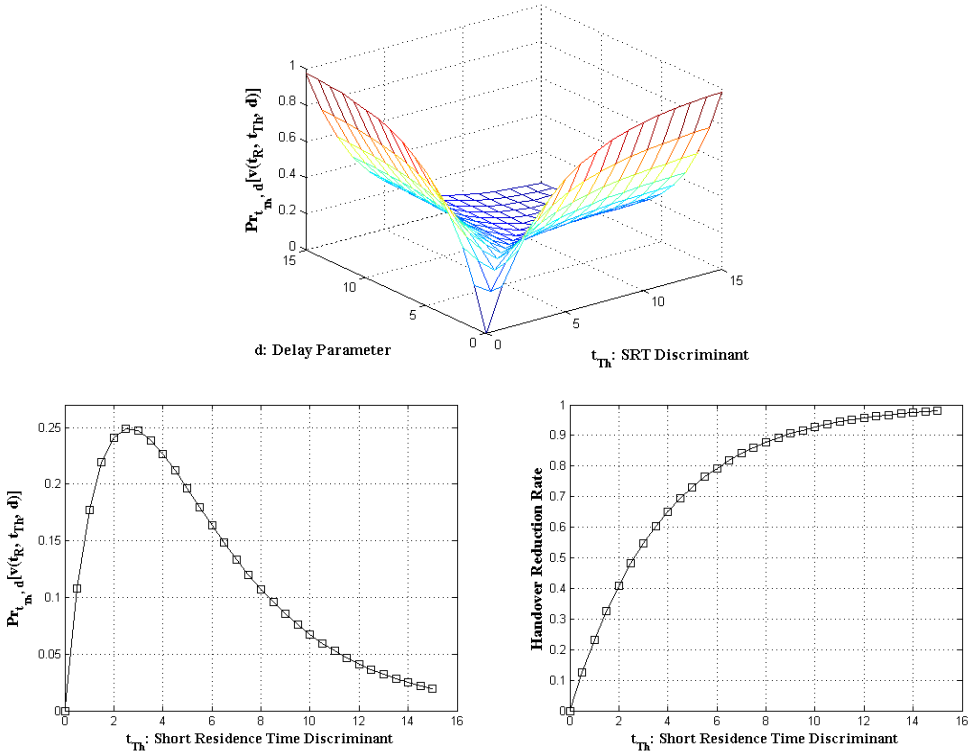


Fig. 6. The numerical results for $t_R \sim WEB(3.8, 0.9965)$: (a) incorrect handover decision probability according to t_{Th} and d (b) incorrect handover decision probability according to t_{Th} (c) handover reduction probability according to t_{Th}.

Fig. 6 shows the numerical results of *Weibull* distribution for the eq. (4.4). We can see that all plots are very similar to those of the *Exponential* distribution case. This is because the eq. (4.2) and (4.4) have very similar shapes to each other. Hence, the above results can be explained in the same manner as in the *Exponential* distribution case.

Fig. 7 shows the numerical results of *Pareto* distribution for the eq. (4.5). Since the pdf of *Pareto* distribution is monotonic decreasing, for all value of t_{Th}, the incorrect handover decision probability is minimized when $d = t_{Th}$. The notable thing of here is that the changing speed is slower than in other distribution cases. That is why t_R is more uniformly distributed (even at the range of few hours or few days) compared to other distribution cases. In other words, due to the long-tail property of *Pareto* distribution, the portion of short-residence time users is lower than other distribution cases. The long-tail property makes the effects of t_{Th} weaken on $Pr[v(t_R, t_{Th}, d) = 0]$ and R_h. Therefore, the efficacy of delay based AC may be degraded in *Pareto* distribution case.

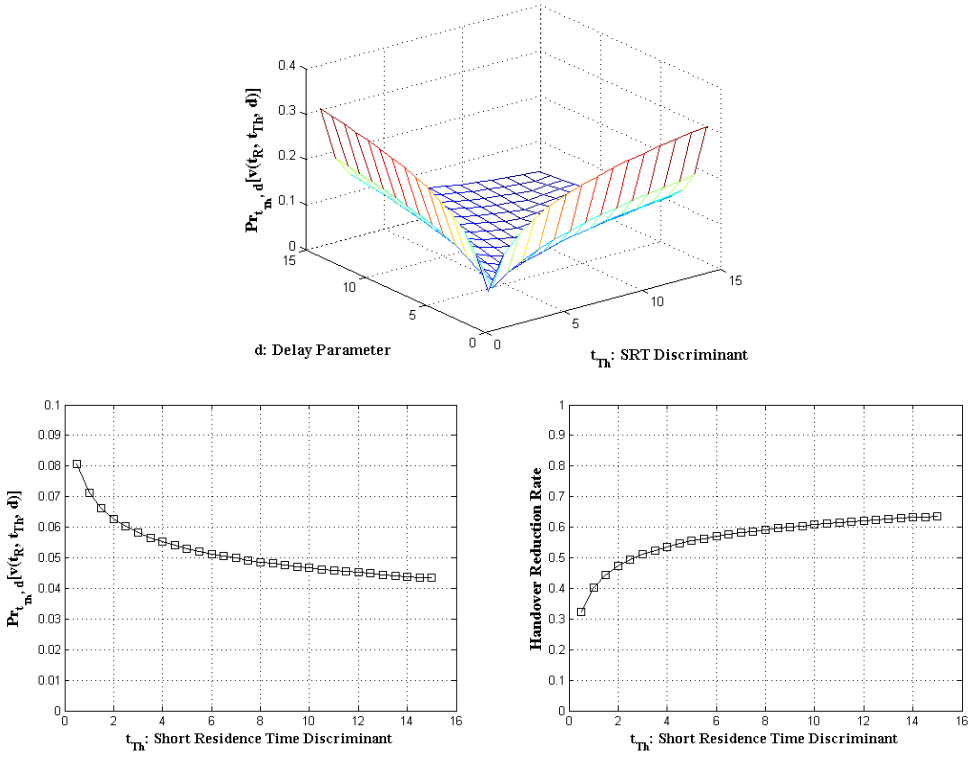


Fig. 7. The numerical results for $t_R \sim P(I)(0.183, 0.06)$: (a) incorrect handover decision probability according to t_{Th} and d (b) incorrect handover decision probability according to t_{Th} (c) handover reduction probability according to t_{Th}.

5. Design Insights

From above numerical observations, we derive two important insights which can be helpful to determine the optimal delay parameter in terms of incorrect handover decision probability. They are expressed as following two theorems.

Theorem 2 If the pdf of t_R is a monotonic increasing, the incorrect handover decision probability decreases as d decreases.

***Proof*:** Let us assume α which is between $(0, t_{Th}]$. The equation (3.4) when $d = \alpha$ is

$$Pr[v(t_R, t_{Th}, \alpha) = 0] = \int_{\alpha}^{\alpha+t_{Th}} f_{t_R}(t)dt. \tag{4.6}$$

And, when $d = \alpha - \delta$ ($0 < \delta < \alpha$), the equation (3.4) is

$$Pr[v(t_R, t_{Th}, \alpha - \delta) = 0] = \int_{\alpha-\delta}^{\alpha-\delta+t_{Th}} f_{t_R}(t)dt. \tag{4.7}$$

Now, when we subtract the eq. (4.7) from (4.6), we obtain

$$\begin{aligned}
&\int_{\alpha}^{\alpha+t_{Th}} f_{t_R}(t)dt - \int_{\alpha-\delta}^{\alpha-\delta+t_{Th}} f_{t_R}(t)dt \\
&= \int_{\alpha}^{\alpha+t_{Th}} f_{t_R}(t)dt - (\int_{\alpha-\delta}^{\alpha} f_{t_R}(t)dt + \int_{\alpha}^{\alpha+t_{Th}} f_{t_R}(t)dt - \int_{\alpha+t_{Th}-\delta}^{\alpha+t_{Th}} f_{t_R}(t)dt) \\
&= \int_{\alpha+t_{Th}-\delta}^{\alpha+t_{Th}} f_{t_R}(t)dt - \int_{\alpha-\delta}^{\alpha} f_{t_R}(t)dt.
\end{aligned} \tag{4.8}$$

Since $\alpha - \delta < \alpha < \alpha + t_{Th} - \delta < \alpha + t_{Th}$ and $f_{t_R}(t)$ is monotonic increasing,

$\int_{\alpha+t_{Th}-\delta}^{\alpha+t_{Th}} f_{t_R}(t)dt - \int_{\alpha-\delta}^{\alpha} f_{t_R}(t)dt > 0$ due to the property of integration. In short, the eq. (4.7) is always smaller than (4.6). ■

Theorem 3 If the pdf of t_R is a monotonic decreasing, the incorrect handover decision probability is minimized when $d = t_{Th}$.

***Proof*:** when $d = t_{Th}$, the eq. (3.4) is

$$Pr[v(t_R, t_{Th}, t_{Th}) = 0] = \int_{t_{Th}}^{2t_{Th}} f_{t_R}(t)dt. \tag{4.9}$$

And, when $d = t_{Th} - \delta$ ($0 < \delta < t_{Th}$), the equation (3.4) is

$$Pr[v(t_R, t_{Th}, t_{Th} - \delta) = 0] = \int_{t_{Th}-\delta}^{2t_{Th}-\delta} f_{t_R}(t)dt. \tag{4.10}$$

Now, when we subtract the equation (4.9) from (4.10), we obtain

$$\begin{aligned}
&\int_{t_{Th}-\delta}^{2t_{Th}-\delta} f_{t_R}(t)dt - \int_{t_{Th}}^{2t_{Th}} f_{t_R}(t)dt \\
&= \left(\int_{t_{Th}-\delta}^{t_{Th}} f_{t_R}(t)dt + \int_{t_{Th}}^{2t_{Th}} f_{t_R}(t)dt - \int_{2t_{Th}-\delta}^{2t_{Th}} f_{t_R}(t)dt\right) - \int_{t_{Th}}^{2t_{Th}} f_{t_R}(t)dt \\
&= \int_{t_{Th}-\delta}^{t_{Th}} f_{t_R}(t)dt - \int_{2t_{Th}-\delta}^{2t_{Th}} f_{t_R}(t)dt
\end{aligned} \tag{4.11}$$

Since $t_{Th} - \delta < t_{Th} < 2t_{Th} - \delta < 2t_{Th}$ and $f_{t_R}(t)$ is monotonic decreasing, $\int_{t_{Th}-\delta}^{t_{Th}} f_{t_R}(t)dt - \int_{2t_{Th}-\delta}^{2t_{Th}} f_{t_R}(t)dt > 0$ due to the property of integration. In short, the eq. (4.9) is always smaller than (4.10). ■

The theorem 2 and 3 show the optimal delay parameter is determined differently upon the shape of the pdf of t_R and the value of t_{Th}. For example, if the pdf of t_R increases until an inflection point p and thereafter decreases, the solution of the eq. (3.4) is 0 when $t_{Th} < p$. However, when $t_{Th} > p$, the solution is t_{Th}. These two properties are useful hints for designing the proper delay parameter. If the system administrator knows that the pdf of t_R is monotonic increasing or decreasing, he/she does not have to solve the equation (3.4) explicitly. All he/she has to do is choosing one from just two candidates: 0 for when the pdf is increasing and t_{Th} for when the pdf is decreasing.

6. Conclusion

In hierarchical cellular systems, reducing unnecessary handover is an important issue because many inter-tier handovers may cause significant burden to the macro base station. Therefore, some recently proposed handover schemes adopt the delay based AC which delays the macro → small cell handovers for pre-determined waiting time to prevent short-term residence time users being unnecessarily handed to the small cell. In such delay based AC, determining the proper delay parameter is important matter because if too long or too short delay parameter causes the system makes undesirable actions such as wrong allowances of unnecessary handovers, or wrong avoidance of necessary handovers. To quantify this issue, we introduce a new performance metric referred to *incorrect handover decision probability* which balances trade-offs between the occurences of the above two undesirable situations. By using the incorrect handover decision probability as the objective function, we express the proper delay parameter decision problem as an minimization problem that can be easily solved numerically. From the extensive numerical evaluations and probabilistic analysis, we find out two important insights: (a) the smaller delay parameter is better if the pdf of t_R is monotonic increasing (b) the optimal delay parameter is equivalent to the discriminant t_{Th} if the pdf of t_R is monotonic decreasing. In other words, when the probabilistic distribution function of t_R is

monotonic, we do not have to solve the minimization problem. All we have to do is simply choosing the one between two candidates: 0 and t_{Th}. This property will be a helpful reference when a network operator designs a delay based AC protocol for hierarchical macro-small cellular system. We hope that a future research discovers further useful properties about the incorrect handover decision probability functions especially for when an input distribution function is not monotonic.

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