A Cache Scheme for Femtocell Reselection

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***Abstract*—In a cellular network, femto base stations may be deployed to improve indoor coverage that cannot be accommodated by the macro base stations. However, to switch from the macro-tier to the femto-tier, a user equipment may be required to scan the whole femto radio spectrum, which is an expensive operation. We propose a cache scheme that may significantly speed up the macro-tier to femto-tier switching.**

***Index Terms*—Femtocell, cell reselection.**

I. Introduction

IN a cellular network, macrocells and femtocells form a two-tier architecture. We may deploy macro base stations (BSs) in the highways without femto BSs. On the other hand, a deep building with poor/no reception of macro BSs may be covered by low-power femto BSs. In some areas, a macro BS may overlay with hundreds of femto BSs.

This letter studies the femtocell reselection issue when a user equipment (UE) moves from a macro BS to a femto BS. Consider a CDMA network utilizing the scrambling codes for radio communications. When a UE is first turned on, it scans all carrier frequencies of the assigned spectrum, and searches for an appropriate scrambling code (and thus a BS) for camping. After the UE has camped on a cell, it continues to listen to the broadcast of the BS. The broadcast includes a neighbor list that consists of the the neighbor cell information (e.g., frequencies and scrambling codes). According to the cell information, the UE repeats measuring the signal strengths of neighbor cells. When the camp-on cell's signal is too weak, the UE may reselect and switch to a better cell. To switch from a femto BS to the macro BS is simple. We only need to include the macro BS's information in the femto BSs' neighbor cell lists (a femto BS typically overlays with one macro BS). When the UE scans the neighbor cell list, the macro BS is eventually selected if tier-switching is required. On the other hand, to switch from the macro BS to a femto BS is not trivial because macro BS may overlay with more femto BSs than the size of its neighbor cell list (which is limited to 32 inter-frequency BSs [1]). Therefore, the neighbor cell list of a macro BS does not likely to include any femto BSs. In this case, to switch from the macro-tier to the femto-tier, the UE may be required to scan the whole femto radio spectrum, which is an expensive operation.

This letter describes a cell reselection cache scheme to speed up the macro-tier to femto-tier switching. We propose analytical and simulation models to investigate the performance of the cache scheme.

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II. The Cache Scheme

The cache scheme for femtocell reselection is basically the same as the least recently used (LRU) scheme for computer cache or BS routing [3]. The cache stores the cell information of the recently visited femto BSs when the UE moves to the macro-tier. The size of each cached entry is less than 28 bytes [1]. When the UE returns to the femto-tier, the BSs in the cache are searched in the most recently visited order. It is important to determine the cache size so that the recently visited femto BSs can be captured without consuming too much memory. In cell reselection, we investigate the number of BSs to be scanned before a BS is selected, which is quite different from memory access cost in computer cache. Let $\Pr[n]$ be the probability that when a UE returns from the macro-tier to the femto-tier, the entrance femto BS is found in the n-th entry of the cache, where the cache size is $N \geq n$. In this case, the cost for the UE to camp on a femtocell is n. Let M be the number of BSs in the femto radio spectrum. If a cache miss occurs, the maximum number of the remaining BSs to be scanned is $M - N$, and the average scanning cost is $\frac{M-N}{2}$ under the uniform random assumption. The camp-on cost in this case is

$$N + \frac{M-N}{2} = \frac{M+N}{2}$$

Therefore, a general expression for the expected camp-on cost C is

$$C = \sum_{n=1}^{N} n \Pr[n] + \left(\frac{M+N}{2}\right)\left(1 - \sum_{n=1}^{N} \Pr[n]\right). \quad (1)$$

Since it takes about 180ms to scan an inter-frequency BS, the camp-on delay is $180C$ ms.

Probability $\Pr[n]$ for a specific UE can be obtained by tracing the UE's movement history. We note that "user movement locality" and "memory access locality" are different, which also distinguish our work from a typical computer cache study. We consider three user movement models as follows:

Model I. In one-dimensional movement with move-right probability p, a UE moves to the right with a fixed probability p and moves to the left with probability $1-p$, which is similar to the model described in [4]. The camp-on cost is denoted C_I.

Model II. In one-dimensional movement with move-back probability p, a UE turns back to the femto BS where it came from with probability p. That is, if its last movement is to the right, then its next movement is to the left with probability p, and to the right with probability $1-p$. The camp-on cost is denoted C_{II}.

Model III. In two-dimensional movement with move-back probability p, the buildings have a Manhattan-street layout (i.e., a mesh structure where a UE moves to one of

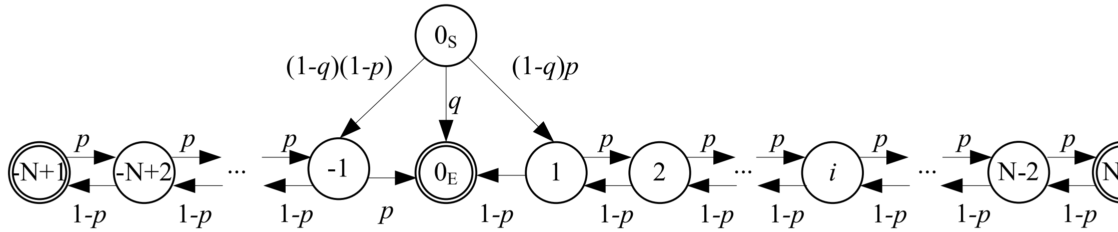

Fig. 1. State transition diagram for UE movement with move-right probability p (where $N \geq 2$).

the four directions). The UE moves back to the femto BS where it came from with probability p, and to the BS in each of the other three directions with probability $\frac{1-p}{3}$. The camp-on cost is denoted C_{III}.

We analytically derive $\Pr[n]$ for Model I. We also develop a simulation model based on the event-driven approach widely adopted in mobile network studies [4]. The analytic model is used to validate the simulation for Model I, and then the validated simulation is extended to accommodate Models II and III.

In Model I, buildings are located in a line labeled by i, and the UE visits these buildings with the state transition diagram illustrated in Figure 1. Let BS_i be the entrance femto BS to Building i. In this diagram, state i represents that the UE stays in Building i, except that we use two states 0_S (Start) and 0_E (End) to describe the behavior of the UE in Building 0. The UE initially resides in femto BS_0 (at state 0_S). The UE may visit other femto BSs of the building and then it moves from BS_0 to the macro-tier. When it moves back to the femto-tier, it visits BS_0 again (i.e., a state transition $0_S \to 0_E$) with probability q (where $0 \leq q < 1$). It enters BS_1 (i.e., a transition $0_S \to 1$) with probability $(1-q)p$, and enters BS_{-1} (i.e., a transition $0_S \to -1$) with probability $(1-q)(1-p)$, where $0 < p < 1$. For $-N < i \neq 0 < N$, the UE resides at BS_i (and therefore Building i) for a while, and eventually moves to the macro-tier. When it visits the femto-tier again, it enters BS_{i+1} with probability p, and enters BS_{i-1} with probability $(1-p)$. The starting state is 0_S, and the ending states are 0_E if the UE eventually moves back to BS_0 (i.e., BS_0 is found in the cache), and N and $-N$ if the UE moves to BS_N/BS_{-N} without visiting BS_0 (i.e., BS_0 is not found in the cache). In this model, $\Pr[n]$ (where $n > 1$) can be interpreted as the probability that starting from BS_0, the UE visits exactly $n-1$ distinguished BSs (other than BS_0) before it moves back to BS_0. In Figure 1, there are two one-dimension random walks: one with states $(0_E, 1, 2, ..., N-1)$ where the absorbing states are 0_E and $N-1$, and the other with states $(0_E, -1, ..., -N+1)$ where the absorbing states are 0_E and $-N+1$. The solution for each of them is equivalent to that for Gambler's Ruin Problem.

Consider the random walk with states $(0_E, 1, 2, ..., N-1)$, where $N \geq 2$. Denote $\mu_k(p,n)$ $(1 < n \leq N)$ as the probability that starting from BS_k $(0 \leq k \leq n-1)$, the UE visits at most $n-1$ distinguished BSs and reaches BS_{n-1} before it visits BS_0. For $0 < k < n-1$, we obtain the following equations

$$\mu_k(p,n) = p\mu_{k+1}(p,n) + (1-p)\mu_{k-1}(p,n) \quad (2)$$

and obviously,

$$\mu_0(p,n) = 0, \text{ and } \mu_{n-1}(p,n) = 1 \quad (3)$$

From Figure 1, it is clear that $\mu_1(p,1) = q$. For $n > 1$, we obtain $\mu_1(p,n)$ by solving (2) and (3) as follows:

$$\mu_1(p,n) = \begin{cases} \dfrac{n-1}{n} & , p = 0.5 \\ \dfrac{p^{n-1}(1-p) - (1-p)^n}{p^n - (1-p)^n} & , p \neq 0.5 \end{cases} \quad (4)$$

Similarly, for the random walk with states $(-N+1, ..., -1, 0_E)$, we can obtain probability $\mu_1(1-p,n)$ by using (4).

For $n = 1$, $\Pr[1] = \mu_1(p,1) = q$. For $n > 1$, from (4) and the state transition diagram in Figure 1, $\Pr[n]$ is derived as

$$\begin{aligned} \Pr[n] &= (1-q)\left\{p\left[\mu_1(p,n) - \mu_1(p,n-1)\right]\right. \quad (5) \\ &\quad \left. + (1-p)\left[\mu_1(1-p,n) - \mu_1(1-p,n-1)\right]\right\} \\ &= \begin{cases} \dfrac{1-q}{n(n-1)} & , p = 0.5 \\ \dfrac{2(1-q)(2p-1)^2(1-p)^{n-1}p^{n-1}}{[p^{n-1} - (1-p)^{n-1}][p^n - (1-p)^n]} & , p \neq 0.5 \end{cases} \quad (6) \end{aligned}$$

By applying (6) to (1), we obtain the camp-on cost C_I for Model I as

$$C_I = q + \frac{(M+N)(1-q)}{2} \quad (7)$$
$$- \begin{cases} (1-q)\left\{\sum_{n=2}^{N}\left[\dfrac{M+N-2n}{2n(n-1)}\right]\right\} & , p = 0.5 \\ (1-q)(2p-1)^2\left\{\sum_{n=2}^{N} \dfrac{(M+N-2n)(1-p)^{n-1}p^{n-1}}{[p^{n-1} - (1-p)^{n-1}][p^n - (1-p)^n]}\right\} & , p \neq 0.5 \end{cases} \quad (8)$$

Note that the above analysis follows standard queueing modeling, which applies to any "BS_0" that the UE visits [2]. The analytic model is validated against the the simulation experiments, where the discrepancy of C_I between the analytic and simulation models is within 0.1%.

III. Numerical Examples and Conclusion

This section studies the performance of the cache scheme. We assume that probability $p = 0.7$ and $q = 0.1$. For other p, q values, similar results are observed and are not presented.

Figure 2 illustrates the effects of N/M on C, where $M = 480$ and $p = 0.7$. In Model I, C_I decreases and then increases

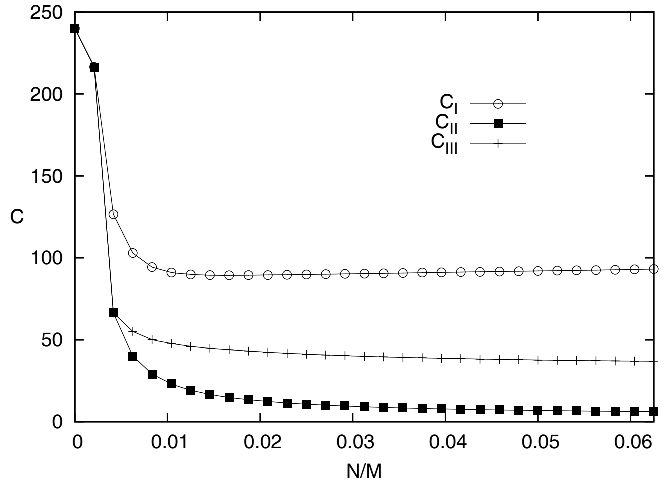

Fig. 2. Effects of user movement models and N/M on C ($q = 0.1, M = 480, p = 0.7$).

as N/M increases. When N/M is small, increasing N will partially capture the locality of the UE. However, $p = 0.7$ implies that the UE tends to move to the right, and when $N \geq 1$, there is a probability $1 - \sum_{n=1}^{N} \Pr[n]$ that the UE's locality is never captured, which contributes to C_I and make it an increasing function of N/M. The "$\circ$" curve indicates that even if the UE tends to move to one direction (i.e., the locality is not good), the femtocell reselection procedure still benefits from a cache of small size (e.g., $0.01M$).

In both Models II and III, when N is small, the costs C_{II}/C_{III} significantly decrease as N/M increases. This phenomenon implies that increasing the cache size can effectively capture the locality of the UE. When N is large, to increase N only has negligible benefit. When $N \approx 0.05M$, the UE almost always finds the BS in the cache, and adding more cache capacity does not improve the hit ratio.

In summary, to take the advantage of the cache for all mobility patterns studied in this letter, a cache of size around 0.01M (i.e., the number of BSs accommodated in the radio spectrum) is appropriated. For example, if $M = 480$, then $1\%M \approx 5$ entries in the cache will yield good hit performance.

IV. Acknowledgements

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