Analysis for the Enhanced Cell Reselection Mechanism in Heterogeneous Wireless System

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Abstract This work proposes an enhanced algorithm for cell reselection mechanism in heterogeneous wireless system. A Markov model-based analytical method is proposed to describe system behavior and derive performance metric. The optimal QoS control parameter for the algorithm is derived based on system model and analyzed in numerical results. It is shown that the network performance can be improved by utilizing the proposed algorithm, and the optimal value of QoS control parameter varies according to system traffic condition, which provides insight for network deployment and radio resource management.

1 Introduction

The cell reselection process of user equipment (UE) is an important physical-layer process of cellular wireless communication system. It is defined and described in third generation partner project (3GPP) physical layer specifications [1, 2], and essentially specifies UE's behavior to choose other access cells when the power or quality of the received signal varies. In tradition, simple scenarios of cellular system like global system for mobile communication (GSM) system or third generation (3G) wideband code division multiple access (WCDMA) system, the radio access network (RAN) is constituted by the so-called macrocells, where the base station (BS) or node B (NB) serves as the access point for UEs in a wide coverage area. In that case, the cell reselection behavior happens when UE moves through the edge of different cells and requires handoff to the cell with best access quality. This scenario can be construed as homogeneous wireless system. With the emergence of fourth generation (4G) long-term evolution (LTE) standard and its rapid deployment

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around the world, more complex network scenarios unlike traditional homogeneous wireless system are introduced and referred as the heterogeneous wireless systems.

The concept of heterogeneity and its related theories have become heated research topics in the past decade. In the family of 3GPP cellular systems, the typical scenario of heterogeneous wireless system consists of GSM system: enhanced data rate for GSM evolution (EDGE) system, WCDMA system, LTE system, and even in the future, fifth generation (5G) system. Within theses systems, different nodes are involved such as pico nodes and femto nodes, along with macro nodes deployed in a overlapping manner. To make the scenario more complicated, the wireless local area network (WLAN) system are also considered in heterogeneous wireless system, since the convergence of different radio access technologies (RATs) is a fundamental aspect for 3GPP cellular system and an inevitable trend of future wireless communication system. These conditions provide a much more complicated scenario for UE mobility management problem, in which the cell reselection problem has already become an important technique applied in current cellular wireless systems as well as an interesting theoretical research point.

In the field of mobility management and radio resource management (RRM) research, the Markov-related model is extensively studied and discussed in existing literatures [3–7] due to its accuracy, simplicity and validity, and is considered to be an ideal research methodology to model the cell reselection mechanism in heterogeneous wireless system. In this work, we first present the proposed mechanism for cell reselection in heterogeneous wireless system defined in 3GPP specifications, then derived a Markov mode-based analytical method for the system to obtain system performance metric, then provide detailed analysis for optimal parameter in the algorithm.

The paper is organized as follows: in Sect. 2 the cell reselection mechanism in [1] and the proposed algorithm is described. Then in Sect. 3 we present the mathematical model for the system, and derived the optimal parameter solutions to the model. Section 4 presents the main results for the optimal quality of service (QoS) parameter analysis. Section 5 concludes the paper.

2 Enhanced Cell Reselection Mechanism for Heterogeneous Wireless System

2.1 Cell Reselection Mechanism in 3GPP TS 36.304

We first present cell reselection process defined in the latest technical specification (TS) [1] in 3GPP protocol in a mathematical manner. This protocol is essentially designed for 3GPP cellular wireless system. To provide more theoretical insight, we model the system in a general manner. Consider 4G LTE system and its evolution scenario, where adjacent macro evolved node Bs(MeNBs) form wide-area coverage for UEs in each corresponding cell (macro cell), and low power nodes (LPNs) within each cell form hot-spot coverage. The criterion for UE to perform cell reselection is the value of reference signal power denoted by P_k, where k denotes the index of different types of nodes and cells. In real application scenarios, all overlapping RAT cells in the heterogeneous wireless system have the rank of priority, according to which UE will perform cell reselection to the specific cell when P_k meets certain thresholds requirements. Priority rank parameters are broadcasted to all UE by system information or dedicated signallings [1].

For UE that has camped on others' cells adjacent to cell k, if P_k is large enough, the UE will try to reselect to cells k for better access service. Define T_k^{in} as the threshold for P_k when UE tries to camp on cell k, above which UE will try to perform cell reselection to cell k. For UE already camped on cell k, if P_k is too small, it will try to reselect to other cells. Define T_k^{out} as the threshold for P_k when UE tries to camp on other cells, below which UE will try to perform cell reselection to other cells. Assume UE currently camps on cell k, and try to perform cell reselection to other cells with different priority ranks. Let the cell with index h represent the cell with higher priority, and let the cell with index l represent the cell with lower priority. The algorithm for cell reselection is summarized as follows:

- If $P_h > T_h^{in}$ holds for a consecutive time $t_{reselection}$, UE shall perform cell reselection from cell k to cell h.
- If $P_l > T_l^{in}$ and $P_k < T_k^{out}$ hold for a consecutive time $t_{reselection}$, UE shall perform cell reselection from cell k to cell l.

If more than one cell meets the above requirements, UE shall perform cell reselection to the cell with highest priority.

2.2 Enhanced Algorithm for Admission Control

Consider the scenario where 4G LTE MeNB or LPN nodes bear large amount of traffic and has potential risk of data congestion. The admission control mechanism is needed to prevent overload and protect QoS for UEs. We derive our new algorithm on the basis of previous algorithm in [7] for general heterogeneous wireless environment. Consider the scenario when cell k is overload and admission control is needed. We aim to prevent UEs in other cell to perform cell reselection to cell k and encourage UEs on the edge of cell k to perform cell reselection to other cells. When overload happens in cell k, an indicator bearing the index of k is broadcasted to all UEs within the system in the same manner as the rank of priority parameters for the purpose of informing UEs to initiate the admission control mechanism for cell k.

Define multiplication factor $\phi \in [0, 1]$. UE will adjust thresholds for cell reselection to achieve admission control as follows:

- For all UEs:
  - replace T_k^{in} with $T_k^{in} \times (1 + \phi)$, and replace T_k^{out} with $T_k^{out} \times (1 - \phi)$.
  - replace T_l^{in} with $T_l^{in} \times (1 - \phi)$.
  - replace T_h^{in} with $T_h^{in} \times (1 - \phi)$.
- For UEs in cell l that meet $P_k > T_k^{in} \times (1 + \phi)$, UE performs cell reselection to cell k with probability $Pr^{in}(P_k, T_k^{in}, \phi)$
- For UEs in cell k that meet $P_h > T_h^{in} \times (1 - \phi)$, UE performs cell reselection to cell h with probability $Pr^{in}(P_h, T_h^{in}, \phi)$
- For UEs in cell k that meet $P_l > T_l^{in} \times (1 - \phi)$ and $P_k < T_k^{out} \times (1 - \phi)$, UE performs cell reselection to cell l with probability $Pr^{out}(P_k, T_k^{out}, \phi)$
- For UEs in cell h that meet $P_k > T_k^{in} \times (1 + \phi)$ and $P_h < T_h^{out} \times (1 - \phi)$, UE performs cell reselection to cell k with probability $Pr^{out}(P_h, T_h^{out}, \phi)$

The function $Pr^{in}(P, T, \phi)$ and $Pr^{out}(P, T, \phi)$ represent the probability of UEs to perform extra reselection behavior according to the proposed algorithm. To maintain consistency with 3GPP protocols, the function should be an interpolation between the probability of [0, 1] in the domain of $[T, T \times (1 + \phi)]$ and $[T \times (1 - \phi), T]$. ϕ represents the admission control intensity. Let ρ denote the order of polynomial interpolation which is not deeply discussed in this paper, and $U(x)$ denotes the unit step function. Denote $T \times (1 + \phi)$ as $\hat{T}$, and $T \times (1 + 0.5\phi)$ as T_m. We propose the following theorem for the functions:

Theorem 1 *Define polynomial interpolation of* $Pr^{in}(P, T, \phi)$ *and* $Pr^{out}(P, T, \phi)$ *as follows:*

$$Pr^{in}(P, T, \phi) = \mathbb{P} \times U(P - T) + (1 - \mathbb{P}) \times U(P - \hat{T}). \quad (1)$$

$$Pr^{out}(P, T, \phi) = (\mathbb{P} - 1) \times U(P - T) - \mathbb{P} \times U(P - \hat{T}) + 1. \quad (2)$$

$$\mathbb{P} = 0.5 \left[\left(\frac{P - T}{0.5\phi T} \right)^{\rho} - 1 \right] U(T_m - P) + 0.5 \left[1 - \left(\frac{\hat{T} - P}{0.5\phi T} \right)^{\rho} \right] U(P - T_m) \quad (3)$$

When $\phi \to 0$ *and* $\rho \to \infty$*, the proposed algorithm will degrade to the original cell reselection algorithm.*

Proof By performing some algebra manipulations, the polynomial interpolation function will degrade to step function $U(P - T)$ with $\phi = 0$ and $\rho \to \infty$, which is equivalent to the function for the original cell reselection algorithm. □

3 Optimal Parameter Analysis Model

3.1 Markov Chain-Based System Model

In order to evaluate the performance of our proposed model, we utilize Markov model to describe system behavior. Due to limitation of space, we adopt a simple co-sited integrated LPN–MeNBs heterogeneous wireless system where two MeNBs serve as macrocells for 4G LTE and 3G CDMA RANs, and one LPN in the center of the cell serves for hot-spot coverage. The radius of 4G LTE MeNB cell is assumed to be larger than LPN cell and smaller than 3G CDMA cell. We leave more complicated scenarios where MeNB is coupled with various LPN nodes and adjacent MeNBs for future work. To model the system behavior, we adopt the Markov model and define the three-dimension state vector as follows:

$$\mathbf{s} = (n_{3G}, n_{4G}, n_{LPN}), \tag{4}$$

where n_{3G}, n_{4G}, and n_{LPN} denote the numbers of UEs camped on 3G CDMA MeNB cell, 4G LTE MeNB cell and LPN cell, respectively, with their maximum load number denoted by n_{3G}^{MAX}, n_{4G}^{MAX}, and n_{LPN}^{MAX}, respectively.

The mobility of UEs is described by the arrival rates of events that occur when UEs perform powering on or off and choose the best cell to camp on, as known as cell selection, or when UEs move through the edges of the cells and perform cell reselection. Those events are modeled as the Poisson process for analysis convenience. For simplicity we assumed that $T_k^{out} = T_k^{in} = T_k$, and adopt the simplified path loss model and ignore fading impacts. Let d_k denotes the radius of cell k, we have the following equation:

$$T_k = P_t K \left[\frac{d_0}{d_k}\right]^{\gamma}, \tag{5}$$

where P_t denotes the transmission power of the node, K denotes the constant determined by antenna parameters and average channel loss, and d_0 denotes the reference distance of antenna in far field. In such scenario, T_k multiplied by $(1 \pm \phi)$ in the algorithm in Sect. 2.2 is equivalent to d_k multiplied by $(1 \pm \phi)^{-\frac{1}{\gamma}}$.

To model events in the system based on geology assumptions above, denote λ^N as the arrival rate of event per unit area in which case new UEs power on and perform cell selection. Also, denote μ as the departure rate for UEs that power off and leave the system. For 3G CDMA MeNB cell, 4G LTE MeNB cell and LPN cell, the corresponding arrival rates of new UEs are given as follows:

$$\lambda_{3G}^N = \lambda^N \times \pi(d_{3G}^2 - d_{4G}^2), \tag{6}$$

$$\lambda_{4G}^N = \lambda^N \times \pi(d_{4G}^2 - d_{LPN}^2), \tag{7}$$

$$\lambda_{LPN}^{N} = \lambda^{N} \times \pi d_{LPN}^{2}. \tag{8}$$

For each cell, the corresponding departure rate of events in which case UEs power off is denoted by $\mu_{3G} = \mu \times n_{3G}$, $\mu_{4G} = \mu \times n_{4G}$ and $\mu_{LPN} = \mu \times n_{LPN}$ respectively.

Denote λ_k^R as the arrival rate of event per unit in which case UEs perform cell reselection when roaming through the edge of cell k. Consider the ring area on the edge of the cell, the number of UEs within this ring is proportional to its size. Thus the rates of cell reselection events are given as follows:

$$\lambda_{3G-4G}^{R} = \lambda^{R} \times \frac{2\pi d_{4G} \times \Delta d_{4G}}{\pi\left(d_{3G}^{2} - d_{4G}^{2}\right)} \times n_{3G}, \tag{9}$$

$$\lambda_{4G-3G}^{R} = \lambda^{R} \times \frac{2\pi d_{4G} \times \Delta d_{4G}}{\pi\left(d_{4G}^{2} - d_{LPN}^{2}\right)} \times n_{4G}, \tag{10}$$

$$\lambda_{4G-LPN}^{R} = \lambda^{R} \times \frac{2\pi d_{LPN} \times \Delta d_{LPN}}{\pi\left(d_{4G}^{2} - d_{LPN}^{2}\right)} \times n_{4G}, \tag{11}$$

$$\lambda_{LPN-4G}^{R} = \lambda^{R} \times \frac{2\pi d_{LPN} \times \Delta d_{LPN}}{\pi d_{LPN}^{2}} \times n_{LPN}, \tag{12}$$

where Δd_k denotes the width of the ring on the edge of cell k, and $2\pi d_k \times \Delta d_k$ denotes the estimated size of the ring.

$$P_{\mathbf{mn}} = \begin{cases} \lambda_{3G}^{N}/\lambda_{sum}, & \text{if } n_{3G} = m_{3G}+1, n_{4G} = m_{4G}, n_{LPN} = m_{LPN} \\ \lambda_{4G}^{N}/\lambda_{sum}, & \text{if } n_{3G} = m_{3G}, n_{4G} = m_{4G}+1, n_{LPN} = m_{LPN} \\ \lambda_{LPN}^{N}/\lambda_{sum}, & \text{if } n_{3G} = m_{3G}, n_{4G} = m_{4G}, n_{LPN} = m_{LPN}+1 \\ \lambda_{3G-4G}^{N}/\lambda_{sum}, & \text{if } n_{3G} = m_{3G}-1, n_{4G} = m_{4G}+1, n_{LPN} = m_{LPN} \\ \lambda_{4G-3G}^{N}/\lambda_{sum}, & \text{if } n_{3G} = m_{3G}+1, n_{4G} = m_{4G}-1, n_{LPN} = m_{LPN} \\ \lambda_{4G-LPN}^{N}/\lambda_{sum}, & \text{if } n_{3G} = m_{3G}, n_{4G} = m_{4G}-1, n_{LPN} = m_{LPN}+1 \\ \lambda_{LPN-4G}^{N}/\lambda_{sum}, & \text{if } n_{3G} = m_{3G}, n_{4G} = m_{4G}+1, n_{LPN} = m_{LPN}-1 \\ \mu_{3G}/\lambda_{sum}, & \text{if } n_{3G} = m_{3G}-1, n_{4G} = m_{4G}, n_{LPN} = m_{LPN} \\ \mu_{4G}/\lambda_{sum}, & \text{if } n_{3G} = m_{3G}, n_{4G} = m_{4G}-1, n_{LPN} = m_{LPN} \\ \mu_{LPN}/\lambda_{sum}, & \text{if } n_{3G} = m_{3G}, n_{4G} = m_{4G}, n_{LPN} = m_{LPN}-1 \\ 0, & \text{otherwise} \end{cases}. \tag{13}$$

3.2 Dynamic Equations and Performance Metric

For a given state, its transition behavior depends on the cumulation of all possible Poisson events. To describe the transition probability of the state vector, define

Table 1 Parameters configuration

Parameter	Value	Parameter	Value	Parameter	Value
d_{3G}	1.2 km	n_{3G}^{MAX}	10	ρ	1
d_{LTE}	1.0 km	n_{4G}^{MAX}	10	ϕ	0–0.5
d_{LPN}	0.6 km	n_{LPN}^{MAX}	10	η	0.8
λ^N	0.12–0.22/s/km^2	λ^R	0.1/s/km^2	μ	0.01/s/km^2
γ	2.2	Q^S	1	θ	0.5
Δd_k	$0.01 \times d_k$				

cumulative event rate as follows:

$$\lambda_{sum} = \lambda_{3G}^N + \lambda_{4G}^N + \lambda_{LPN}^N + \lambda_{3G-4G}^N + \lambda_{4G-3G}^R + \lambda_{4G-LPN}^R + \lambda_{LPN-4G}^R + \mu_{3G} + \mu_{4G} + \mu_{LPN}. \tag{14}$$

For the state transition from state $\mathbf{m} = (m_{3G}, m_{4G}, m_{LPN})$ to state $\mathbf{n} = (n_{3G}, n_{4G}, n_{LPN})$, its transition probability denoted by $P_{\mathbf{mn}}$ conforms to the cumulation characteristics of Possion process and is given as Eq. (13).

Let $p_{\mathbf{n}}$ denote the static probability of state $\mathbf{n}$. The static probability conforms the constraints in Eq. (15) and can be solved by numerical methods.

$$p_{\mathbf{n}} \geq 0, p_{\mathbf{n}} = \sum_{\mathbf{m}} P_{\mathbf{m},\mathbf{n}} \times p_{\mathbf{m}}, \sum_{\mathbf{n}} p_{\mathbf{n}} = 1, \forall \mathbf{n}. \tag{15}$$

Due to the limitation of space, we only present the QoS analysis method for the system. Consider the evaluation for the average QoS for cell k. For non-congestion traffic status, define Q^S as the standard QoS value for each UE. If the number of UEs camping on the cell is too large, the average QoS of UEs in the cell is likely to be degraded and the system needs to perform admission control. Define overload fraction factor $\eta \in (0, 1)$, and QoS penalty factor $\theta \in (0, 1)$. If $n_k > \eta n_k^{MAX}$ holds, the QoS value for each UE is degraded to be θQ^S. Hence the average QoS metric for the system is denoted by the Eq. (16). Apparently, the reselection control intensity ϕ and the order of interpolation ρ will affect the system performance and reflects on the value of Q_k. Thus, the optimal parameter in the enhanced cell reselection mechanism for admission control of cell k is given in Eq. (17).

$$Q_k = \sum_{n_k > \eta n_k^{MAX}} p_{\mathbf{n}} n_k \theta Q^S + \sum_{n_k \leq \eta n_k^{MAX}} p_{\mathbf{n}} n_k Q^S \tag{16}$$

$$\phi^* = \arg\max_{\phi} [Q_k(\phi, \rho)], \phi \in [0, 1] \tag{17}$$

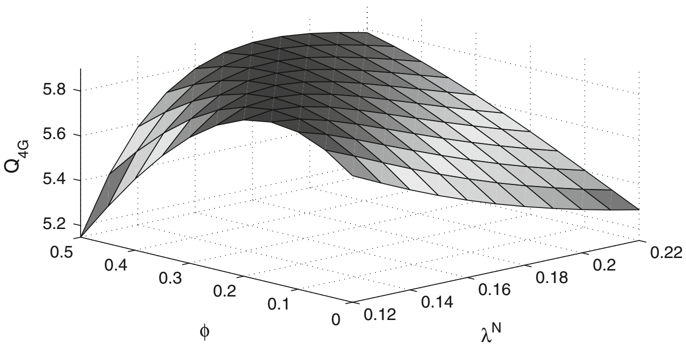

Fig. 1 Impact of ϕ on average QoS for 4G cell

4 Numerical Results

The parameters of the network model is configured as shown in Table 1. We set the maximum UE number to be very small to avoid the well-known computation complexity of Markov model. Due to limited space of this work, we leave the complex model and its solution for future work. The result for average QoS metric for 4G cell is shown in the following figure (Fig. 1). As we can see, the optimal admission control intensity parameter ϕ varies in different traffic condition. Also, if ϕ is too large the performance will degrade since the admission control algorithm affects UEs within the local cell. If ϕ is too small, the algorithm will not effectively prevent overload and achieve best performance. The optimal ϕ can be obtained by numerical methods when utilizing our algorithm.

5 Conclusion

In this work, we propose the enhanced algorithm for cell reselection in heterogeneous wireless system and the analytical model to evaluate system performance. Numerical result shows that the proposed algorithm achieves best performance when assigned a suitable parameter of admission control intensity. Further work includes more complex mathematical model and parameter scenarios for the system, and effective methods to evaluate the performance in such complex system scenarios.

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