This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2005 proceedings.

Performance Analysis of the 3G Network with Complementary WLANs

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Abstract — An analytical modeling method is developed for the evaluation of integrated 3G/WLAN networks. To adapt the feature of the emerging wireless networks efficiently and to cover many possible situations in reality, the cell residence times are modeled generally. The channel occupancy times, the horizontal and vertical handoff rates as well as some interesting performance measures are derived and calculated. Both analysis and numerical results show that the performance of the 3G network is significantly increased when the integrated 3G/WLAN network is employed, and that the performance of integrated 3G/WLAN network is improved greatly when the WLANs are in the hot-spot areas. The method developed here is expected to be useful for modeling and performance evaluation of other type of networks, such as the 3G network with the infrastructureless-mode WLANs or ad-hoc networks.

Keywords — Horizontal Handoff, Vertical Handoff, 3G/WLAN Networks, Call Admission Control (CAC), Channel Occupancy Time, Traffic Analysis.

I. INTRODUCTION

Future wireless networks will generally be characterized by heterogeneity in radio access technologies. Currently developing 3G technologies such as UMTS, cdma2000 and TD-SCDMA will provide to mobile users wide coverage area. However, the costs of acquiring the necessary radio spectrum and the network equipment upgrades are very high. In the same time, wireless local area networks (WLANs) continue to proliferate in corporate and residential environments due to their low-cost, high-speed wireless Internet access for the localized hot spots. The IEEE 802.11 family has dominated in the United States and is now extending worldwide. In Europe, ETSI has developed a competing standard HiperLan2 [1]. However, the coverage offered by WLANs is quite limited and they lack roaming support.

The complementary characteristics of 3G networks (slow, wide coverage) and WLANs (fast, limited coverage) make it attractive to integrate the two technologies to provide ubiquitous wireless access. The 3G networks provide global coverage, mobility and quality of service (QoS), while WLANs are designed to cover localized hot-spot areas, such as airport, shopping center, hotel, etc. Although the WLAN is subject to its small area and limited mobility, it can substantially increase the capacity and performance of the associated 3G networks. Handoffs will be possible (with some trade-off in performance and service) between the 3G network and WLANs.

There are many possible interworking approaches between WLAN and 3G networks [2-5]. For any type of interworking approach, a multimode 3G/WLAN mobile terminal is required. The mobile terminal should have at least two logical air-interfaces: Uu-interface (same as the definition by 3GPP) for communications with a Node B at 2GHz (3G band) and Ur-interface (not yet defined in 3GPP) for communications with an access point (AP) at 2.4GHz or 5GHz band. Since the Ur-interface works at different frequency band, it has almost no interference to the transmission signal at the Uu-interface. Some channels in the WLAN-worked band can be reserved for servicing 3G-related sessions, so that the integrated 3G/WLAN network can provide more capacity and better performance while does not consume more bandwidth (of a 3G system) than a conventional 3G network (i.e., without WLANs). In other words, an incoming request blocked will be dropped immediately in the conventional 3G network but not necessarily dropped in the integrated 3G/WLAN network. Following this idea, we build our mathematics model in next section for performance evaluation of the integrated network.

Six interworking scenarios were described in [2]. The connectivity between cdma2000 and 802.11 networks was studied by a loosely-coupled interworking in [3]. In [4], an internetworking architecture for HiperLan2 and UMTS networks was proposed. In [5], the complementary use of WLANs in conjunction with UMTS was presented. The capacity of the integrated system has been shown to significantly increase by a set of simulation tools when interworking between hotspots and 3G networks is employed. This is particularly true when a high percentage of the area is covered by the hot-spots. Unfortunately, all the above approaches for performance evaluation of the integrated network are based on simulation modeling, where the simulation parameters selected may become critical and cause a bias on the model or even make it leave the bounds of reality. Furthermore, to the best of our knowledge, there has been no performance evaluation approach based on analytical modeling for the same work. This is the focus on this paper. Specifically, we are interested in determining the quantitative performance measures of the integrated network based on general distribution of channel occupancy time for different classes of users and different types of sessions.

The rest of the paper is organized as: section 2 proposes a mathematics model fitting the integrated architecture; section 3 presents the detailed analysis in terms of handoff arrival rates, channel occupancy times, steady-state probabilities and performance measures; section 4 presents the numerical results; and section 5 concludes the paper.

II. MODEL DESCRIPTON

Consider an integrated 3G/WLAN network consisting of a number of 3G cells. Within each cell there are some isolated

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Hot-spots located by WLANs.

Assume that there are two user classes in the integrated network. The 3G users have a relative low bandwidth requirement and arbitrary mobility feature, while the WLAN users have a high bandwidth requirement and limited mobility feature. The 3G users can always attempt a horizontal handoff among neighboring 3G cells (just as handoff in conventional cellular networks) when they reach the boundary of a cell. In addition, if there is no channel available, the 3G users can attempt a vertical handoff to one of the underlying WLANs through the reserved channels in the WLAN. After successfully making a vertical handoff, the call may complete in the WLAN, or continue to attempt a take-back vertical handoff to the 3G cell when the user moves out of the WLAN. However, the WLAN users are assumed to move only within the WLAN coverage, and no horizontal handoff can be made since the WLANs are isolated at hot-spot places. For simplicity, we assume that the WLAN users don’t attempt vertical handoffs to the 3G cell due to their limited moving range and there is no channel exclusively reserved for WLAN users in the 3G cell. However, if a WLAN user moves out of the WLAN, he can change his terminal’s Ur-interface to Uu-interface to request a call, in such a way he will become another class of user (i.e., 3G user) and the request will become a new call request in the 3G cell.

Due to the limited resource in wireless communications, the call with different priority should be treated differently in resource allocation. A handoff call is usually given a higher priority over a new call to maintain a lower handoff dropping probability. Assume there are M channels in each 3G cell, of which m channels is the maximum value allowed for new calls. This simple channel allocation scheme is widely used in literature [6, 7] and called new call bounding scheme in [6]. Assume there are K channels in the WLANs under a 3G cell, of which K-K_v channels are assigned exclusively for the calls of WLAN users and K_v channels are reserved exclusively for vertical handoff calls of 3G users. Thus, when rejection occurs under a call admission control (CAC) strategy: a new call of 3G users may directly attempts a vertical handoff to the underlying WLAN if it happens to be in the WLAN’s coverage (we call this *directly vertical handoff*). Otherwise, the system will search one of the ongoing calls under the WLAN’s coverage and make it attempt a vertical handoff and release the channel to serve for the request call (we call this *indirectly vertical handoff*); a horizontal handoff call has no chance to attempt a directly vertical handoff (since WLANs are isolated within a 3G cell, rather than on the boundary of it). Then, the CAC strategies in the 3G cell and the WLANs are as follows.

The 3G cell:

- A new call of 3G users is rejected and attempts a vertical handoff (directly or indirectly) when there are m ongoing new calls of 3G users or all the M channels are busy.
- A horizontal handoff call of 3G users is rejected and attempts an indirectly vertical handoff when all the M channels are busy.
- A take-back vertical handoff call of 3G users is rejected when all the M channels are busy (the take-back vertical handoff call is assumed to have the same priority as the horizontal handoff call).

The WLANs:

- A new call of WLAN users is rejected when there are K-K_v ongoing calls of WLAN users in the WLAN.
- A vertical handoff call of 3G users is rejected when there are already K_v ongoing vertical handoff calls in the WLAN.

III. PERFORMANCE ANALYSIS

In this section, we analyze the performance of the integrated network in terms of handoff arrival rates, channel occupancy times, steady-state probabilities and performance measures. Assume that all the 3G cells and underlying WLANs are stochastically identical, so we can focus our analysis on one 3G cell and underlying WLANs. The various time variables are denoted as follows. Let H and H_{WL} denote call holding times of 3G users and WLAN users with mean h and h_{WL}, and R_{3G} and R_{WL} denote cell residence times of 3G users in a 3G cell and the WLAN with mean r_{3G} and r_{WL}, respectively. Arbitrary variable X has its residual time variable X^r, mean $E[X]$, pdf $f_X(t)$, cdf $F_X(t)$ and the Laplace transform $f_X^*(s)$.

A. The Handoff Arrival Rates

Assume that each arrival process is Poisson. There are three types of calls in a 3G cell: new calls (with rate Λ_n), horizontal handoff calls (with rate Λ_{hh}) and take-back vertical handoff calls (with rate Λ_{vh}), and two types of calls in the WLANs: calls of WLAN users (with rate λ_n) and vertical handoff calls of 3G users (with rate λ_{vh}).

Consider the 3G cell. The horizontal handoff requests may be from the following three cases: a) new calls not blocked in neighboring 3G cells continue their sessions to the current cell; b) horizontal handoff calls having successfully handed off into neighboring 3G cells continue their sessions to the current cell; c) take-back vertical handoff calls in the neighboring 3G cells continue their sessions to the current cell. Thus, the following equation should hold in steady state:

$$\Lambda_{hh}=\Lambda_n(1-P_{3G}^{n})P(R_{3G}^{r}<H)+\Lambda_{hh}(1-P_{3G}^{hh})P(R_{3G}<H^{r}) \\ +\Lambda_{vh}(1-P_{3G}^{vh})P(R_{3G}^{r}<H^{r}), \qquad (1)$$

where $P(R_{3G}^r < H)$ is the probability that a new call initiated from a 3G cell attempts to handoff, $P(R_{3G} < H^r)$ is the probability that a horizontal handoff call attempts to handoff, and $P(R_{3G}^r < H^r)$ is the probability that a take-back vertical handoff call attempts to handoff (note that a vertical handoff call has already dwelled some period time in a 3G cell through the underlying WLAN). By using Laplace transform approach, these probabilities can be calculated as

$$P(R_{3G}^r < H) = \int_0^\infty \int_t^\infty f_H(\tau) f_{R_{3G}^r}(t)\, d\tau dt = \frac{r_{3G}\left[1-f_{R_{3G}}^*(h)\right]}{h}.$$

$$P(R_{3G} < H^r) = \int_0^\infty \int_t^\infty f_{H^r}(\tau) f_{R_{3G}}(t) d\tau dt = f^*_{R_{3G}}(h),$$

$$P(R^r_{3G} < H^r) = \frac{r_{3G}\left[1 - f^*_{R_{3G}}(h)\right]}{h},$$

Therefore, Λ_{hh} can be determined as

$$\Lambda_{hh} = [\Lambda_n(1 - P^n_{3G}) + \Lambda_{vh}(1 - P^{vh}_{3G})] \frac{r_{3G}[1 - f^*_{R_{3G}}(h)]}{h[1 - (1 - P^{hh}_{3G}) f^*_{R_{3G}}(h)]}. \tag{2}$$

In the WLAN, the incoming vertical handoff calls may be from the following sources: a) a new arrival call to a 3G cell blocked will attempt a directly vertical handoff to the WLAN if it is under the WLAN's coverage; otherwise, it will attempt an indirectly vertical handoff to the WLAN; b) a horizontal handoff arrival call to a 3G cell blocked will attempt an indirectly vertical handoff to the WLAN.

For convenience, let us define a special WLAN, which is equivalent to all the WLANs under the same 3G cell. Let γ ($0 \le \gamma \le 1$) denote the *coverage rate* (i.e., the ratio between the area of the equivalent WLAN and that of the 3G cell). Since WLANs represent the hot-spots in a 3G cell, the users in hot-spot area usually have larger population density. For example, 20% of the hot-spot WLAN coverage rate maybe include 50% (rather than 20%) of the population of mobile users in the 3G cell. Thus, when we compute the probability that a mobile terminal is under the WLAN's coverage, we should give a weight factor ω to depict the hot-spot feature, such that $\omega \ge 1$ and $0 \le \omega\gamma \le 1$. Let's denote by p the *population coverage rate* and $p = \omega\gamma$, clearly $p \ge \gamma$ (the equal sign represents the uniform traffic in the cell and $\omega = 1$). Hence, the vertical handoff arrival rate is

$$\lambda_{vh} = \Lambda_n P^n_{3G}\{p + (1 - p)[1 - (1 - p)^{\overline{m}}]\} + \Lambda_{hh} P^{hh}_{3G}[1 - (1 - p)^M], \tag{3}$$

where $\overline{m}$ denotes the current number of ongoing calls in the 3G cell when an incoming new call can not be served. At that situation, there must be at least m users in the cell, i.e., $m \le \overline{m} \le M$. Then, the take-back vertical handoff arrival rate Λ_{vh} can be calculated by

$$\begin{aligned}\Lambda_{vh} = {} & \Lambda_n P^n_{3G} p(1 - P^{vh}_{WL}) P(R^r_{WL} < H) + \{\Lambda_n P^n_{3G}(1 - p)[1 - (1 - p)^{\overline{m}}] \\ & + \Lambda_{hh} P^{hh}_{3G}[1 - (1 - p)^M]\}(1 - P^{vh}_{WL}) P(R^r_{WL} < H^r),\end{aligned}$$

where $P(R^r_{WL} < H)$ is the probability that a directly vertical handoff call attempts to handoff, $P(R^r_{WL} < H^r)$ is the probability that an indirectly vertical handoff call attempts to handoff. By using Laplace transform approach, these probabilities can be calculated as

$$P(R^r_{WL} < H) = P(R^r_{WL} < H^r) = \frac{r_{WL}[1 - f^*_{R_{WL}}(h)]}{h}.$$

Therefore, Λ_{vh} is determined by

$$\begin{aligned}\Lambda_{vh} = {} & \{\Lambda_n P^n_{3G}\{p + (1 - p)[1 - (1 - p)^{\overline{m}}]\} + \Lambda_{hh} P^{hh}_{3G}[1 - (1 - p)^M]\} \\ & \cdot (1 - P^{vh}_{WL}) \frac{r_{WL}[1 - f^*_{R_{WL}}(h)]}{h}\end{aligned} \tag{4}$$

From equations (2), (3) and (4), we can obtain the explicit solutions of different handoff arrival rates, or use the iterative algorithm presented in [8] to solve the fixed-point equations.

B. The Channel Occupancy Times

In order to get tractable analytical results, researchers usually use the exponential distribution to model time variables in wireless networks. However, recent studies showed that the commonly used assumption of exponentially distributed channel occupancy time does not hold for emerging mobile networks [9-11]. Accordingly, we assume the cell residence times of 3G users in a 3G cell and in the underlying WLAN have general distributions, and use the Laplace transform approach to analyze the channel occupancy times. This analytical approach is applied very popularly in wireless networks [7, 11]. Assume that the requested call holding times of 3G users and WLAN users are exponentially distributed. Then the channel holding times for new calls, horizontal handoff and take-back vertical handoff calls of 3G users are

$$T^n_{3G} = \min\{H, R^r_{3G}\}, \quad T^{hh}_{3G} = \min\{H^r, R_{3G}\},$$

and $\quad T^{vh}_{3G} = \min\{H^r, R^r_{3G}\}$.

By using the Laplace transform approach, we can determine the means of these time variables

$$E\left[T^n_{3G}\right] = E[T^{vh}_{3G}] = \frac{1}{h} - \frac{r_{3G}}{h^2}\left[1 - f^*_{R_{3G}}(h)\right], \tag{5}$$

$$E\left[T^{hh}_{3G}\right] = \frac{1}{h}\left[1 - f^*_{R_{3G}}(h)\right]. \tag{6}$$

As we know, the WLAN users have a limited mobility and are assumed to be active only within the WLAN. Hence, the channel occupancy time of a call of WLAN users is just its call holding time, i.e., $E[T_{WL}] = 1/h_{WL}$. However, the channel occupancy time of a vertical handoff call of 3G users in the WLAN is a little bit complicated. Due to length limitation, here we simply give the result and leave the derivation in [8]:

$$E[T_{vh}] = \frac{1}{h} - \frac{r_{WL}}{h^2}\left[1 - f^*_{R_{WL}}(h)\right]. \tag{7}$$

C. The Steady-State Probabilities

From the model description and assumptions, we can model the WLAN as a stationary symmetric queue [12], and describe it as a loss system with multi-servers (channels). This system is known to have an insensitivity property, i.e., the stationary probability depends on the service (channel occupancy time) distribution only through its mean [7, 12]. Let $\pi_{WL}(i, j)$ denote the steady state probability that *i* and *j* are the number of calls of WLAN users and the number of vertical handoff calls of 3G users in the equivalent WLAN, respectively. From the theory of loss system [7, 8, 12], we have

$$\pi_{WL}(i, j) = \pi_{WL}(0,0) \frac{(\lambda_n E[T_{WL}])^i (\lambda_{vh} E[T_{vh}])^j}{i!\, j!}, \tag{8}$$

$$(i, j) \in \Omega \equiv \{i \le K - K_v, j \le K_v, i + j \le K\},$$

where $\pi_{WL}(0,0)$ is the normalizing constant given by

$$\pi_{WL}(0,0) = \left[\sum_{i=0}^{K-K_v} \frac{(\lambda_n E[T_{WL}])^i}{i!} \sum_{j=0}^{K_v} \frac{(\lambda_{vh} E[T_{vh}])^j}{j!}\right]^{-1}.$$

Similarly, let $\pi_{3G}(i,j,k)$ denote the steady state probability that *i*, *j* and *k* are respectively the number of new calls, horizontal handoff and take-back vertical handoff calls from 3G users in the 3G cell. Then the steady state probability is

$$\pi_{3G}(i,j,k) = \pi_{3G}(0,0,0)\frac{\left(\Lambda_n E[T_{3G}^n]\right)^i \left(\Lambda_{hh} E[T_{3G}^{hh}]\right)^j \left(\Lambda_{vh} E[T_{3G}^{vh}]\right)^k}{i!\,j!\,k!}, \qquad (9)$$

$(i,j,k) \in \Psi \equiv \{i \le m, j \le M, k \le M, i+j+k \le M\}$,

where $\pi_{3G}(0,0,0)$ is the normalizing constant given by

$$\pi_{3G}(0,0,0) = \left[\sum_{i=0}^{m}\frac{\left(\Lambda_n E[T_{3G}^n]\right)^i}{i!}\sum_{j=0}^{M-i}\frac{\left(\Lambda_{hh} E[T_{3G}^{hh}]\right)^j}{j!}\sum_{k=0}^{M-i-j}\frac{\left(\Lambda_{vh} E[T_{3G}^{vh}]\right)^k}{k!}\right]^{-1}.$$

D. The Performance Measures

The blocking probability of WLAN users, P_{WL}^n, is the probability that the number of channels in the WLAN occupied by WLAN users is equal to *K*-*K*$_v$:

$$P_{WL}^n = \sum_{j=0}^{K_v}\pi_{WL}(K-K_v, j). \qquad (10)$$

It is noteworthy that P_{WL}^n can be further reduced (and also the channel utilization of the WLAN can be improved) by introducing a preemptive priority mechanism (see [13] for details). More specifically, let WLAN users be allowed to use all the channels in the WLAN, while the vertical handoff calls from 3G cell can preempt them within the range of the reserved number of channels. But in this work, we mainly focus on the performance of 3G system with complementary WLANs. We don't want to introduce more complicated analysis to the WLANs.

The handoff failure probability of a vertical handoff call of 3G users to the WLAN, P_{WL}^{vh}, is the probability that all K_v reserved channels in the WLAN are occupied by 3G users:

$$P_{WL}^{vh} = \sum_{i=0}^{K-K_v}\pi_{WL}(i, K_v). \qquad (11)$$

The blocking of a new call of 3G users in a 3G cell occurs when the number of channels occupied by new calls is equal to *m*, or there is no available channel in the 3G cell. Hence, the new call blocking probability of 3G users in a 3G cell is

$$P_{3G}^n = \sum_{j=0}^{M-m}\sum_{k=0}^{M-m-j}\pi_{3G}(m,j,k) + \sum_{i=0}^{m-1}\sum_{j=0}^{M-i}\pi_{3G}(i,j,M-i-j). \qquad (12)$$

The handoff failure probability of a horizontal handoff call of 3G users in a 3G cell, P_{3G}^{hh}, is the probability that all *M* channels in a 3G cell are occupied by 3G users:

$$P_{3G}^{hh} = \sum_{i+j+k=M}\pi_{3G}(i,j,k) = \sum_{i=0}^{m}\sum_{j=0}^{M-i}\pi_{3G}(i,j,M-i-j)\cdot \qquad (13)$$

Obviously, when *m*=*M*, $P_{3G}^n = P_{3G}^{hh}$, this becomes the non-prioritized scheme for a 3G cell.

The handoff failure of a take-back vertical handoff call occurs when all the channels assigned to them in the 3G cell are occupied. If we give the take-back vertical handoff calls the same priority as the horizontal handoff calls, then the handoff failure probability of a take-back vertical handoff call of 3G users in a 3G cell is $P_{3G}^{vh} = P_{3G}^{hh}$.

We have known that a new call (or horizontal handoff call) will not necessarily be dropped in the integrated 3G/WLAN system when it is blocked in the 3G cell. Now we are interested in the final dropping probability of a new call (or horizontal handoff call) of a 3G user, P_{3G}^{DN} (or P_{3G}^{DH}).

When an incoming new call to a 3G cell cannot be served in the cell, the final dropping of that call may come from one of these reasons: a) the user initiating this call is not covered by the equivalent WLAN, and there is no other ongoing call of 3G users under the WLAN's coverage; b) the user initiating this call is not covered by the equivalent WLAN, and there is at least one ongoing call from 3G users under the WLAN's coverage, but the K_v reserved channels in the WLAN are all occupied; c) the user initiating this call happens to be covered by the WLAN, but the K_v reserved channels in the WLAN are all occupied. Therefore, the final dropping probability of a new call is determined by

$$P_{3G}^{DN} = P_{3G}^n\left\{(1-p)(1-p)^{\overline{m}} + (1-p)[1-(1-p)^{\overline{m}}]P_{WL}^{vh} + pP_{WL}^{vh}\right\}, \qquad (14)$$

where $\overline{m}$ is the same as that in equation (3).

Similarly, the final dropping probability of a horizontal handoff call of 3G users is determined by

$$P_{3G}^{DH} = P_{3G}^{hh}\left\{(1-p)(1-p)^M + (1-p)[1-(1-p)^M]P_{WL}^{vh}\right\}. \qquad (15)$$

IV. NUMERICAL RESULTS

In this section, we present numerical results and further discuss the effect of the number of reserved channels K_v and the coverage rate γ on different performance measures. We choose the hyper-Erlang distribution as the distributions of cell residence times, since the hyper-Erlang model is shown to provide a universal approximator to any general distribution of nonnegative random variable [14]. The pdf of a hyper-Erlang random variable and its Laplace transform are given as

$$f(t) = \sum_{i=1}^{N}\alpha_i\frac{(n_i\theta_i)^{n_i}t^{n_i-1}}{(n_i-1)!}e^{-n_i\theta_i t} \text{ and } f^*(s) = \sum_{i=1}^{N}\alpha_i\left(\frac{n_i\theta_i}{s+n_i\theta_i}\right)^{n_i},$$

where $\sum_{i=1}^{N}\alpha_i = 1$, $\alpha_i \ge 0$, $\theta_i \ge 0$, $N > 0$, $n_i \ge 0$ ($i = 1,2, \quad ,N$). Specifically, the parameters are chosen as $N = 2$, $\alpha_1 = 1-\alpha_2 = 0.4$, $n_1 = 3$, $n_2 = 2$, $\theta_1 = 0.45$ and $\theta_2 = 0.35$ for the 3G cell (mean = 3.31 min) , and $\alpha_1 = 1-\alpha_2 = 0.2$, $n_1 = 2$, $n_2 = 2$, $\theta_1 = 0.25$ and $\theta_2 = 0.35$ for the WLAN (mean = 2.73 min). The call holding time is exponentially distributed with mean 2.5 min for 3G users and 2.5 min for WLAN users. The other system parameters are chosen as follows: *M=30*, *m=25*, *K=50*.

Figs. 1-4 study the effects of the reserved channels K_v (with $\Lambda_n = 10$, *p*=0.4) and the coverage rate γ (with $\lambda_n = 10$, K_v=10) on the final dropping probabilities of a new call and handoff call. Due to length limitation, we omit the cases of other performance measures, such as P_{WL}^n and P_{WL}^{vh}.

Fig. 1 shows that P_{3G}^{DN} decreases with the increase of K_v. Since when K_v increases, more new calls of 3G users can make directly or indirectly vertical handoffs to the underlying WLAN rather than being dropped. As a comparison with the conventional 3G network (without WLANs), we set K_v=0 to study the system performance. We can observe that the integrated network has a much better performance than the conventional network from both the final dropping probability and the capability of adapting high intensity traffic (the curve begins to increase at Λ_n =7 in K_v=0 case while at Λ_n =10 in other cases). The similar situation happens in the (horizontal) handoff calls for the same reason in Fig. 2.

Figs. 3 and 4 study the effect of the coverage rate γ with uniform traffic and hot-spot traffic on system performance. Fig. 3 shows that P_{3G}^{DN} decreases as γ increases. The reason is that the increase of γ leads to more chances of directly and indirectly vertical handoffs, so that the calls that blocked will not necessarily be dropped. We also observe that when the coverage rate is increased to a certain value (which varies from various traffic intensity), the performance improving will be little. In addition, when the coverage area has higher population density (hot-spots), the integrated network will get better performance. The above results are consistent with those obtained in [5], where the authors show them by a set of simulation tools. The similar situation happens in the (horizontal) handoff calls for the same reason in Fig. 4.

V. CONCLUSIONS

We have developed an analytical modeling and evaluation method for an integrated 3G/WLAN network. The cell residence times are modeled by general distributions to adapt to flexible mobility environments. The channel occupancy times, horizontal and vertical handoff rates as well as some interesting performance measures are derived and calculated. From the analysis and numerical results, the performance of the 3G network is shown to be significantly improved with complementary WLANs, especially when the WLANs are in hot-spot areas. This conclusion is consistent with that obtained in [5] by simulation modeling method. The analytical modeling method is expected to be useful for the performance evaluation of other type of networks, such as the 3G network with the infrastructureless-mode WLANs or ad-hoc networks.

There are a number of issues in future research: a) study the system performance by distinguishing the session with real-time call and non-real-time call; b) consider variable bandwidth requirements for each type of call; c) consider allowing WLAN users to make vertical handoffs to the 3G cell and to roam to other WLANs.

ACKNOWLEDGEMENT: The authors would like to thank referees for the carefully reading of the original manuscript. Their comments and suggestions have led to a much better presentation of the paper. The second author of the paper would also like to acknowledge that his work is partially supported by the NSF of US with grant No. 0515263 and partially supported by the National Natural Science Foundation of China with contract No. 60474067.

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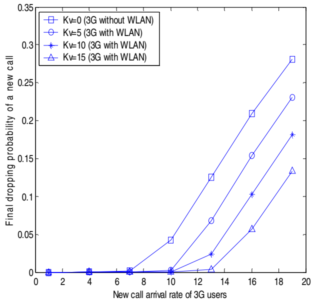

Fig. 1 P_{3G}^{DN} with effect of K_v.

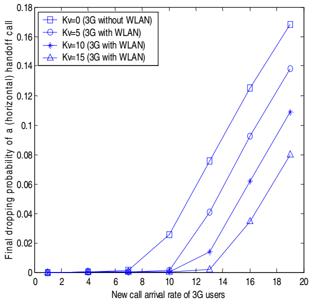

Fig. 2 P_{3G}^{DH} with effect of K_v.

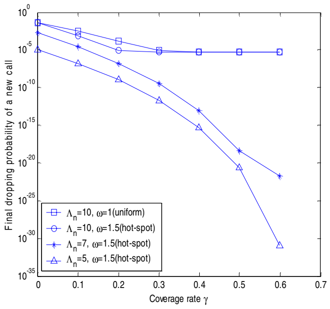

Fig. 3 P_{3G}^{DN} with effect of γ .

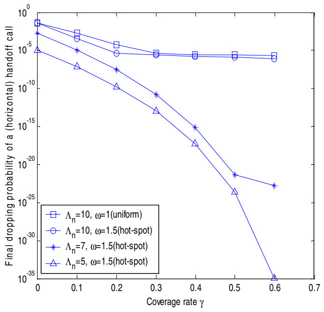

Fig. 4 P_{3G}^{DH} with effect of γ .