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***Abstract*—Design interest for an efficient call admission control (CAC) scheme for a mixed cell (i.e., a 3G cell with embedded WLAN hotspots) is proliferating for the traffic load sharing between 3G and WLAN to improve system capacity and performance as well. Some article proposes CAC schemes to increase 3G system capacity and to reduce dropping probabilities of handoff calls by using WLAN hotspots. Most of the schemes do not consider the vertical handoffs from WLAN to UMTS which is also necessary to fulfill ubiquitous connectivity for some services. In some schemes, the WLAN is not used best way i.e., leaving scenario(s) where a user does not access WLAN under the circumstance in which WLAN can give access to the user(s). We propose a CAC scheme which considers all possible vertical handoff scenarios and provides the fullest usage of WLAN i.e., all users necessarily access WLAN as long as they reside in WLAN coverage. A blocked request (i.e., call) in WLAN is always taken back by overlay 3G system, therefore a request is dropped when all the channels of both 3G and WLAN are busy. We develop an analytical model of proposed CAC scheme and validate it by simulation results. We provide extensive numerical results which show that the model improves not only the 3G performance but also the handoff performance in an entire mixed cell.**

Index Terms—**Call Admission Control (CAC), Embedded WLAN, WLAN hotspot.**

I. INTRODUCTION

Integration of 3rd generation (3G) (e.g. Universal Mobile Telecommunication System (UMTS) [1]) and wireless LAN (WLAN) [2] is thought as one of the solutions to fulfill some of the service demands of next generation networks i.e., fourth generation (4G) networks on hotspot basis. 3G and WLAN are not designed to work together. So, 3G/WLAN integration needs convergence of the two systems at user level, core level and service level. The literature abounds in the field of architectures and mobility management techniques for 3G/WLAN integrated network [3], [4], [5]. The mobility management techniques [5] allow seamless mobility of ongoing sessions from UMTS to WLAN and vice versa.

A UMTS cell containing underlying isolated WLAN hotspots [6] is called a mixed cell. Vertical handoff is a new phenomenon in a mixed cell compared to a pure UMTS cell. A downward vertical handoff occurs when a user having UMTS connection enters a WLAN hotspot [7]. The implementation of this handoff is necessary to provide the users higher bit rates of WLAN. This also transfers load from UMTS to WLAN. As a result, request (i.e., call) handling capacity of a UMTS cell increases nearly three times when 25% of UMTS cell area is covered by underlying WLANs. The capacity gain further improves with increasing user’s density at hotspots [8]. An upward vertical handoff occurs when a user having WLAN session moves out of WLAN coverage. This handoff is necessary to support higher mobility and wider coverage for some services when a user moves out of a WLAN hotspots [8]. For example, a real time voice call can be handed over by UMTS to WLAN and the session can be supported in WLAN through voice over IP (VoIP) [9]. The user with same voice session may move out of a WLAN hotspot and the session can be handed over to UMTS. Similarly, a user downloading large business data file (non real traffic) may leave WLAN hotspot and wish to continue the data session in UMTS. Therefore upward vertical handoff from WLAN to UMTS must be supported. This upward handoff traffic adds to the UMTS traffic. Thus it is essential to consider the upward vertical handoff traffic to capture the net traffic in UMTS. When a user moves from WLAN to UMTS, the user equipment automatically switches to UMTS mode [10] and initiates a request. It is a fresh request in the UMTS system. It needs to be handled with the priority in UMTS because the ongoing WLAN session is now to be made through to UMTS. This WLAN session needs priority in UMTS because a user may move halfway during downloading a large file and termination of the session at that juncture will require a fresh downloading of the large file. So, a user will suffer loss of subscription. Thus an upward vertical handoff request (VHR) must be dealt at least with the priority of horizontal handoff request (HHR) to provide low dropping probability. The CAC scheme proposed in [6] and [7] support only take-back vertical handoff i.e., these schemes support upward handoff for an already vertically handed over session (VHS). Both the schemes do not support the upward vertical handoff for the sessions originated in WLAN. A user has to terminate the WLAN session and initiate a fresh request in UMTS to make the session. Therefore, the schemes do not support mobility support for upward vertical handoff for the users initiating fresh request in WLAN. These scheme also do not support downward vertical handoff in the instant a user moves to WLAN. Rather, CAC schemes permit a user to access WLAN in some special scenarios. The former scheme uses WLAN if a request is blocked in UMTS. So a user is sometimes forced to maintain a UMTS session in WLAN coverage. In later scheme, a user accesses WLAN only when he/she has to initiate HHR. In both the schemes, WLAN is not used to its fullest extent. In [7] a user is not permitted to access WLAN while initiating a new request (i.e., fresh request) (NR). Thus blocking probability does not improve commensurately with increasing WLAN coverage.

We propose an improved call admission control (CAC) scheme for a mixed cell which considers three aspects with their additional features namely, implementation of both upward and downward vertical handoffs for all users, maximum use of WLAN, and a request is dropped only when there is almost no channel in both in WLAN and UMTS. The CAC facilitates users to move between UMTS and WLAN with ongoing sessions. One session can cross UMTS or WLAN more than once. The scheme allows a user to access WLAN as soon as he/she enters a WLAN hot-spot thereby maximizing the change of WLAN access. Users who are already residing in WLAN, always access WLAN for new request (i.e. fresh call) (NR). So, it mandates all users to access WLAN as long as they reside in WLAN coverage providing maximum usage of it. If a downward VHR is blocked the user maintains UMTS session and if an NR is blocked in WLAN alternatively it accesses UMTS (since every hotspot is overlaid with UMTS coverage). Hence some users hold UMTS sessions while staying in WLAN coverage. A blocked request (downward VHR or NR) in UMTS is necessarily dropped.

Hotspots such as restaurant, shopping malls, air ports etc. are usually thickly populated. Users in hotspots generate considerable traffic in a mixed cell. Downward vertical handoffs not only reduces traffic load in UMTS but also lessens horizontal handoff traffic. It reduces the NR arrivals in UMTS as well. Upward vertical handoff provides flexibility to continue movement outside hotspots for some data services. In scheme [7], a blocked downward VHR again initiates upward VHR in UMTS. This is equivalent to an ongoing UMTS session competing for UMTS channel since its downward VHR is blocked. In [13], before downward VHR initiation, the handoff decision incurs exchange of service and networks status between mobile station (MS) and network. This will not only increase the handoff delay but also incorporate system complexity. To overcome these problem, we undertake a simpler downward handoff technique in which a user just takes a chance to avail WLAN facility, and if VHR is blocked it maintains ongoing UMTS session staying in WLAN coverage. We also avoid the indirect VHR scheme in which an UMTS session in WLAN coverage can be transferred to WLAN when any WLAN channel becomes free. Since our scheme allows all users to access WLAN on first priority, the probability is very small that there will be an ongoing UMTS session in WLAN and simultaneously a WLAN channel remains free. Indirect VHR is a network initiated handoff technique and it requires complex control signaling between two networks. Our motto is to implement a mixed cell as far as possible with minimum modification in standards of UMTS and WLAN. So, we neglect indirect VHR scheme to reduce system complexity. Still our model yields improved performance over existing models. We develop an analytical model and validate its performance with simulation results. We provide numerical results of dropping probability of an NR, HHR and VHRs in a mixed cell. It is seen that our model outperforms some models when traffic increases rapidly in a mixed cell.

Rest of the article is organized as follows. Section II presents a brief review of related works. Section III gives the system model describing mobility model, traffic model, and overview of proposed CAC schemes. The estimation of various kind of traffic is given in Section IV. Section V gives the performance analysis providing the steady state probability of data sessions, blocking and dropping probability of requests in a mixed cell. Section VI provides simulation and numerical results and finally, Section VII concludes the articles.

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II. Review of Related Works

The *simulation model* of [8] evaluates the traffic handling capacity of a hybrid cell with underlying WLANs. It is seen that the capacity increases by nearly three times with 25% increment of service area covered by WLAN hotspots in a UMTS cell. The light and medium loaded hotspots can absorb up to 50% of the load of a congested UMTS cell, and the capacity of a UMTS cell increases by 50% [11]. The simulation study in [8] recognizes the effect of users exiting the WLAN with ongoing data sessions which needs to be put into an analytical model.

A resource sharing based call admission control scheme in a cellular/WLAN integrated nework is effective to improve handoff dropping probability [12]. A handoff request can be transferred to cellular system, if it is blocked in WLAN. The call handling algorithm uses resource sharing policy for only handoff requests. Thus, it decreases blocking probability of a handoff request at the expense of increasing blocking probability of fresh request. The vertical handoffs from WLAN to UMTS need to be supported and the related traffic is to be included in the analytical model.

The analytical approach proposed in [13] models the mobility-patters in the 3G-WLAN integrated systems by correlating cell residence time (CRT) in a 3G cell with that in WLAN hotspots. Model is useful to estimate HHR and VHR arrival rates. However, effect of some realistic issues such as the density of users at hotspots need to be considered into the model. The analytical model proposed in [14] considers both voice and data-request through WLANs. A user's access is dependent on admission parameters for efficient grant of voice and data requests in the cellular and WLAN systems. Resource utilization can be maximized under proper load balancing between cellular and WLANs. However, this model requires some new signaling for handoff between cellular and WLAN for exchange of network's information for admission decision.

The survey reveals that the model must support free movement of data sessions from UMTS to WLAN and vice versa to provide ubiquitous communication. The effect of border-WLANs must be included in the model as they reduce the horizontal handoff zone of a UMTS cell. These facts demand more realistic analytical models of UMTS/WLAN integration.

III. Overview of Proposed System Model

A. A Mixed Cell Structure

Figure 1 shows that a hexagonal UMTS cell contains some isolated WLAN hotspots completely within itself. The coverage of all WLAN hotspots in a mixed cell is called equivalent WLAN (Fig. 2). Unless specified, by WLAN we mean equivalent WLAN. Each WLAN cell is connected to UMTS network using loose coupling architecture [5]. Each hotspot is under the dual coverage of UMTS and a WLAN cell. A dual mode MS performs necessary signaling during upward and downward vertical handoffs [15] and vice versa [16]. Depending upon the accessing capability and subscription profiles, the users in mixed cell are classified as follows.

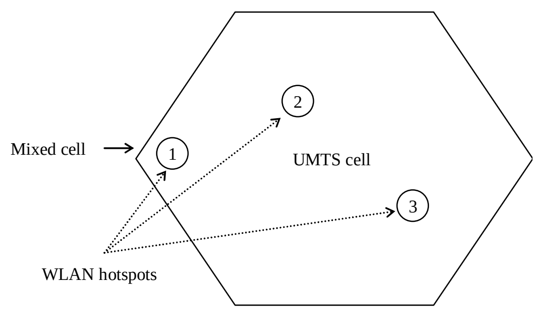
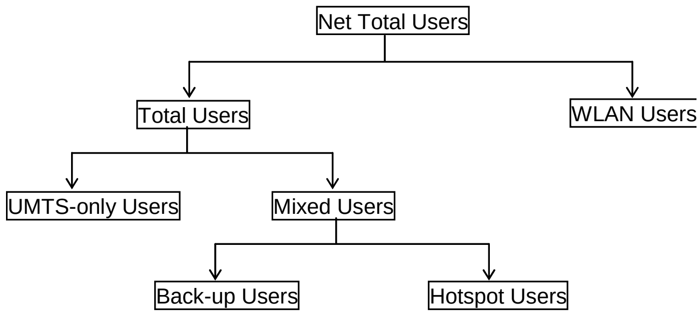


Figure 1. The structure of a mixed cell.

- **UMTS User:** A UMTS user has subscriptions for only UMTS services. He/she cannot access WLAN system even if he/she is within a WLAN hotspot (Chart I).
- **WLAN User**: The users having subscription for only WLAN services are called WLAN users. They cannot use the UMTS system.
- **Mixed User**: A mixed user is a UMTS user having additional subscriptions for WLAN services. Thus, a mixed user can access both the UMTS and WLAN systems.
- **Hotspot User**: The mixed users who are currently residing in WLAN hotspots are called hotspot users. Some hotspot users (with or without ongoing data sessions) may move out of WLAN coverage, and they become back-up users as defined below.

- **Back-up User**: The mixed users who are residing in UMTS-only coverage are called backup users. Some of the back-up users (with or without data sessions) may move to WLAN hotspots and they become hotspot users.
- **Background User**: The *UMTS-only users* and *back-up* users are together called background users. Currently all background users are under UMTS system.
- **Total User:** The sum of background users and hotspots users is called total users i.e., the sum of *UMTS-only users* and *mixed users* is equal to total users.
- **Net Total User**: The sum of UMTS-only users, mixed users and WLAN users is called net total users i.e., the sum of total users and WLAN users is equal to net total users (Chart 1).

Chart 1: Users' classes in a mixed cell.



We define the following parameters in respect of a mixed cell.

A -Ratio of total WLAN coverage in mixed cell to the coverage of a pure UMTS cell.

p - Relative fraction, i.e., ratio of mixed users to total users.

d- Ratio of users' density in WLAN to that in UMTS-only coverage. It is called density ratio.

g - This the ratio of hotspot user to mixed users. It represents the probability that a mixed user is a hotspot user i.e., the probability that a mixed user will reside in WLAN hotspot. We assuime that a mixed user moves from UMTS-only coverage to a WLAN hotspot with the probability of g . It is termed as *coverage probability*.

$$g \approx \frac{1}{[Ad]^{-1} + 1} \tag{1}$$

For detailed derivation see APPENDIX. I. From equation (1), it is seen that g increases with increasing A and d .

B. *Mobility Pattern and Its Model*

Session-Mobility Scenarios: We specify following mobility scenarios of sessions in a mixed cell (Fig. 2).

- A new session (NS) (i.e., a session established by a new request), or a horizontally handed over session (HHS) of a *UMTS-only user* may be completed within the same cell or it may initiate HHR in a neighbor UMTS cell.
- An NS, or an HHS or a VHS (i.e., vertically handed over session) of a *back-up user* may be completed in the UMTS-only coverage of the same cell or it may initiate HHR in neighbor cell or it may initiate VHR in WLAN.
- An NS, or a VHS of *hotspot user* may be completed in WLAN itself or it may initiate VHR in the UMTS-only coverage.
- An NS of a *WLAN user* is always completed in the WLAN itself.

A Use's mobility in a cellular network is characterized by its CRT and its distribution pattern [17]. CRT also influences the cell performance [18], [19]. A user, in a packet data mobile network (i.e., GPRS, UMTS) will occupy a data channel similarly to a typical voice user [20]. Therefore, when a user gets a channel in a UMTS cell, she will use it for the duration of cell residence. Thus, the modeling of radio resource allocation in UMTS networks is similar to the radio channel allocation for personal communication system. Channel holding time (CHT) depends on the user's mobility which is characterized by CRT. The cell shapes specifically UMTS coverage in mixed cells are irregular, and the speed and direction of mobile users are hard to characterize. In recent time, hyper-Erlang distribution is adopted to model the CRT in mobile networks [21], [22], [23]. The hyper-Erlang distribution preserves the Markovian property of the resulting queuing networks models. This also has universal approximation properties. So, field data can be readily used to find the model parameters statistically. We use hiper-Erlang distribution for CRTs in UMTS-only coverage and in WLAN of a mixed cell.

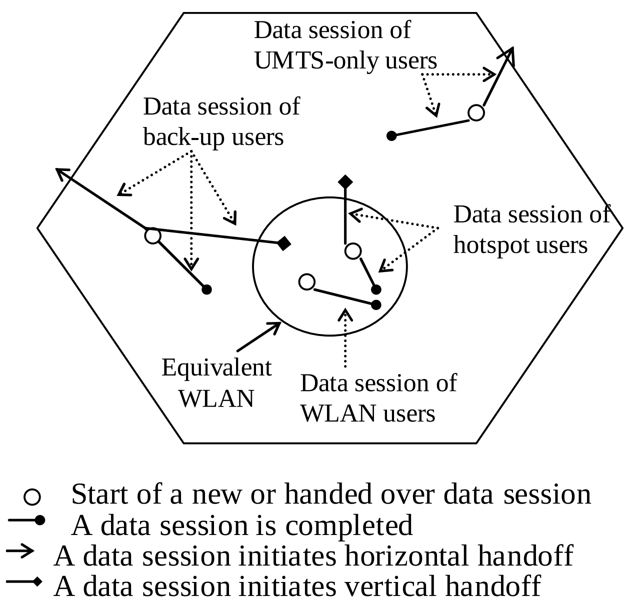


Figure 2. Mobility scenarios in a mixed cell.

Hyper-Erlang Distribution Model: Let t repreent the hyper-Erlang distribution of an arbitray random variable X. Then, the density function of Hyper-Erlang discribution is as follows [21].

$$f_X(t) = \sum_{i=1}^{N} \alpha_i \frac{(n_i\theta_i)^{n_i} t^{m_i-1}}{(m_i-1)!} e^{-m_i\theta_i t} \ (t \geq 0), \tag{2}$$

$$f_X^*(s) = \sum_{i=1}^{N} \alpha_i \left(\frac{n_i\theta_i}{s+n_i\theta_i} \right)^{n_i}, \tag{3}$$

where $f_{R^U}^*(s)$ is Laplace transform of $f_{R^U}(t)$ and $\alpha_i \geq 0$, $\sum_{i=0}^{N} \alpha_i = 1$, and N, n_i and θ_i are positive numbers.

Hyper-Erlang distribution is easier to use than the other models. The k^{th} moment can be computed through Laplace transform approach as follows [22].

$$E[t^k] = (-1)^k f_X^{*(k)}(0) = \sum_{i=0}^{N} \alpha_i \frac{(n_i+k-1)!}{(n_i-1)!} (n_i\theta_i)^{-k} \tag{4}$$

There are two options to use the equation (4): one, the parameters α_i, n_i and θ_i can be estimated by fitting a number of moments from field data; two, expected value (i.e., mean CRT) can be estimated from equation (4) by setting $k=1$ and setting suitable values of parameters α_i, n_i and θ_i. The mean CRT can be used to estimate the mean CHT. We use the second option for performance analysis of a mixed cell.

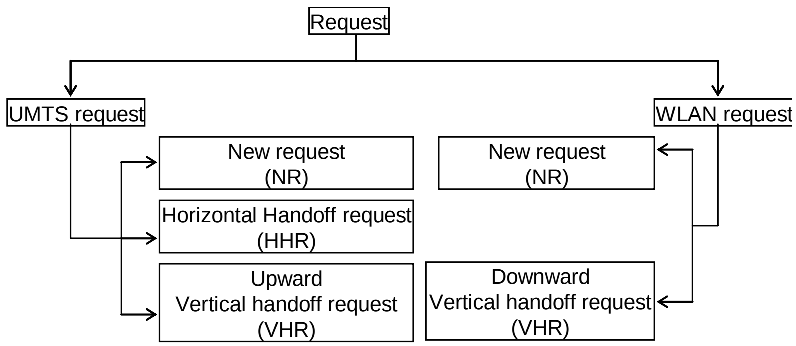
UMTS provides wider coverage with lower bit rates and WLAN provides small coverage with higher bit rates. During a single session, a user is visible to one system (either UMTS or WLAN) at a time. So, we assume separate

CRTs for UMTS and WLAN in a mixed cell. Let R^U and R^W denote CRTs in UMTS and WLAN, respectively, with means $\frac{1}{r^u}$ and $\frac{1}{r^w}$.

C. Traffic and its Model

There are broadly two classes of traffic in a mixed cell, real traffic such as voice traffic and non-real traffic such as elastic data session. We consider same mobility pattern for both the classes of traffic. Each class of traffic is generated by various types of requests as shown in Chart 2. There are two basic types of requests in a mixed cell, UMTS request and WLAN request, and they are generated for UMTS and WLAN systems, respectively. UMTS requests comprise NRs, HHRs and upward VHRs. WLAN requests comprise NRs and downward VHRs. We define the request-life as the duration of time elapsed between the instant a request is initiated and the instant the request is dropped or the session is terminated. During request-life, depending upon the channel availability of the systems and mobility the user a request may undergo certain distinct states. For our model and traffic estimation, we define the following seven states of the requests during a request-life: *arrival*, *blocked*, *dropped*, *successful*, *completion*, *VHR-arrival*, *HHR-arrival* (Figure 3). The scenarios of forced termination of a session due to bad channel condition or system failure are included in *completion* state.

Chart 2: Types of requests in a mixed cell



Arrival: A *request (NR or, HHR* or VHR) attains *arrival* state when it is initiated by a user (Fig. 3).
Blocked: When a request is denied by a system due to non-availability of channel, a request moves from *arrival* to *blocked* state. A blocked request in WLAN can initiate NR in UMTS. So a *blocked* state can transit to *VHR-arrival* state again.
Dropped: A blocked request is dropped in this state. A blocked request in UMTS is necessarily dropped. So, *blocked* state can transit to *dropped* state.
Successful: In *successful* state, data session is established. So an *arrival* state moves to *successful* state.
Completion: In this state, a user's data session is terminated by a user after the completion of the session. A *successful* state can move to *completion* state.
HHR arrival: When a request initiates an HHR in neighbor cell from its *successful state,* it reaches *HHR arrival* state and this becomes a new *arrival*.
VHR arrival: When a request initiates a VHR from its *successful state*, it reaches *VHR arrival* state and this becomes a new *arrival*.

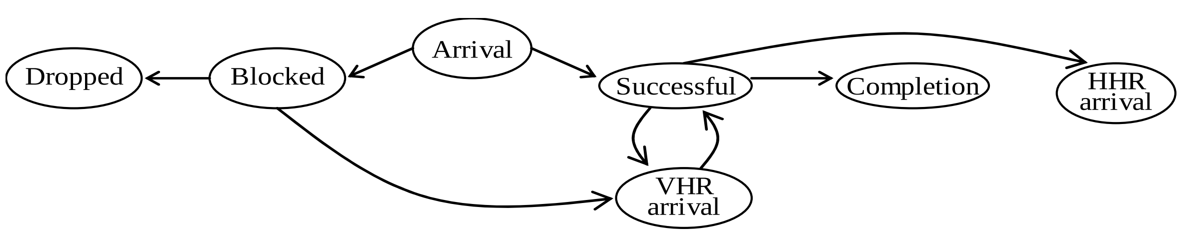


Figure 3. States of requests

Figure 3 shows the state transition scenarios. We represent the session mobility scenario of Figure 2 using state diagram. Obviously, an ongoing data session is represented by the *successful* state of a request. The state transition from *successful* state to next states depends on the type of user initiating a request. For backup users, the *successful* state can transit to any one of three states as shown in Figure 2. For a UMTS-only user, the *successful* state can transit either to *completion* or to *HHR arrival* state because this user cannot initiate VHR in WLAN. For a hotspot user, the *successful* state can transit either to *completion* or to *VHR arrival* state because this user cannot initiate horizontal handoff from WLAN to WLAN. For a WLAN user, the successful state can transit to only *completion* state because a WLAN user cannot access UMTS.

Traffic model: Conversional and interactive are the two most important classes of services which are defined for UMTS [12]. A real-time service having two way communications is called conversional class. A non-real time service is called interactive class. Voice and elastic data services (e.g. web browsing and file transfer) are the typical conversional and interactive classes of services, respectively. Voice service is delay sensitive and requires fixed bandwidth. Elastic data service is tolerant to available bandwidth. Duration of a voice call depends on a user's talk size, but duration of an elastic data call depends on file size and bandwidth availability. If we assume that a data call also uses fixed bandwidth, then data call duration is dependent only on file size. Usually voice and elastic data traffic loads are different because their arrival rates and average call durations are different. Our aim is to design an efficient CAC scheme and to validate its performance. So, for simplicity we assume that in each system (UMTS or WLAN) all call have uniform distribution towards the call duration. However, our model can be applied to estimate voice and data traffic separately. In that case, each class of traffic can be combined to estimate the performance of a mixed cell under simultaneous existence of voice and data calls.

Requests occur according to Poisson's arrival. Request-life has exponential distribution. A session can move between WLAN and UMTS in a mixed cell, or between two UMTS cells. Let H denote the request-life with mean $\frac{1}{h}$.

D. Call admission control scheme

Figure 4 depicts the flow charts for the proposed CAC scheme in a mixed cell. The request handling in UMTS and WLAN systems are explained separately.

In the UMTS system:

- There are total M channels in a UMTS cell out of which maximum m channels (unreserved channels) can be used for NRs and remaining $(M-m)$ channels are reserved for handoffs (HHR and VHR). $m \subseteq M$.
- Both the HHR and VHR are handled with same priority.
- When an arrival of HHR or VHR occurs, the system will try to assign a reserved channel to it. If all reserved channels are already occupied, the system will try to assign an unreserved channel to it. It is blocked if all channels are busy.
- An NR, on its arrival, is blocked if all unreserved channels are occupied.

In a WLAN hotspot:

- In the proposed CAC scheme, there is no reserved WLAN channel for handling VHRs. However, to fit the model for some existing models, we assume that there are total K WLAN channels out which K_v channels are reserved for handling VHRs in WLAN. $K_v \subseteq K$ and in our model, $K_v = 0$.
- Both the NR and VHR are handled with same priority in a WLAN cell.
- An NR or a VHR is blocked if all WLAN channels are busy.
- If an NR is blocked it will initiate a separate NR in UMTS.
- If a VHR is blocked in WLAN, the MS maintains the session in UMTS.

We do not use queuing facility for blocked requests. When an NR is blocked in WLAN, promptly it can try for UMTS without requiring queue in WLAN. When a session moves to WLAN, its wireless network interface card (WNIC) for WLAN works independently. On receipt of WLAN beacons, its WLAN WINC is activated. If it is permitted to access WLAN it triggers off the UMTS WNIC. Then, MS initiates handoff request. This can be implemented using a dual mode MS converged at IP layer so that WLAN link layer can work independently while link layer of UMTS is also active [5]. WLAN MAC function allows one user to access whole bandwidth at a time. It is multi-users with single processor system. We use WLAN as multi servers system as used in [7], [24]. At link layer number of logical channels can be maintained [24]. The number of users can be supported at a time within threshold quality of service (QoS) is the number of logical channels. When a user gets access in WLAN, one logical channel is occupied.

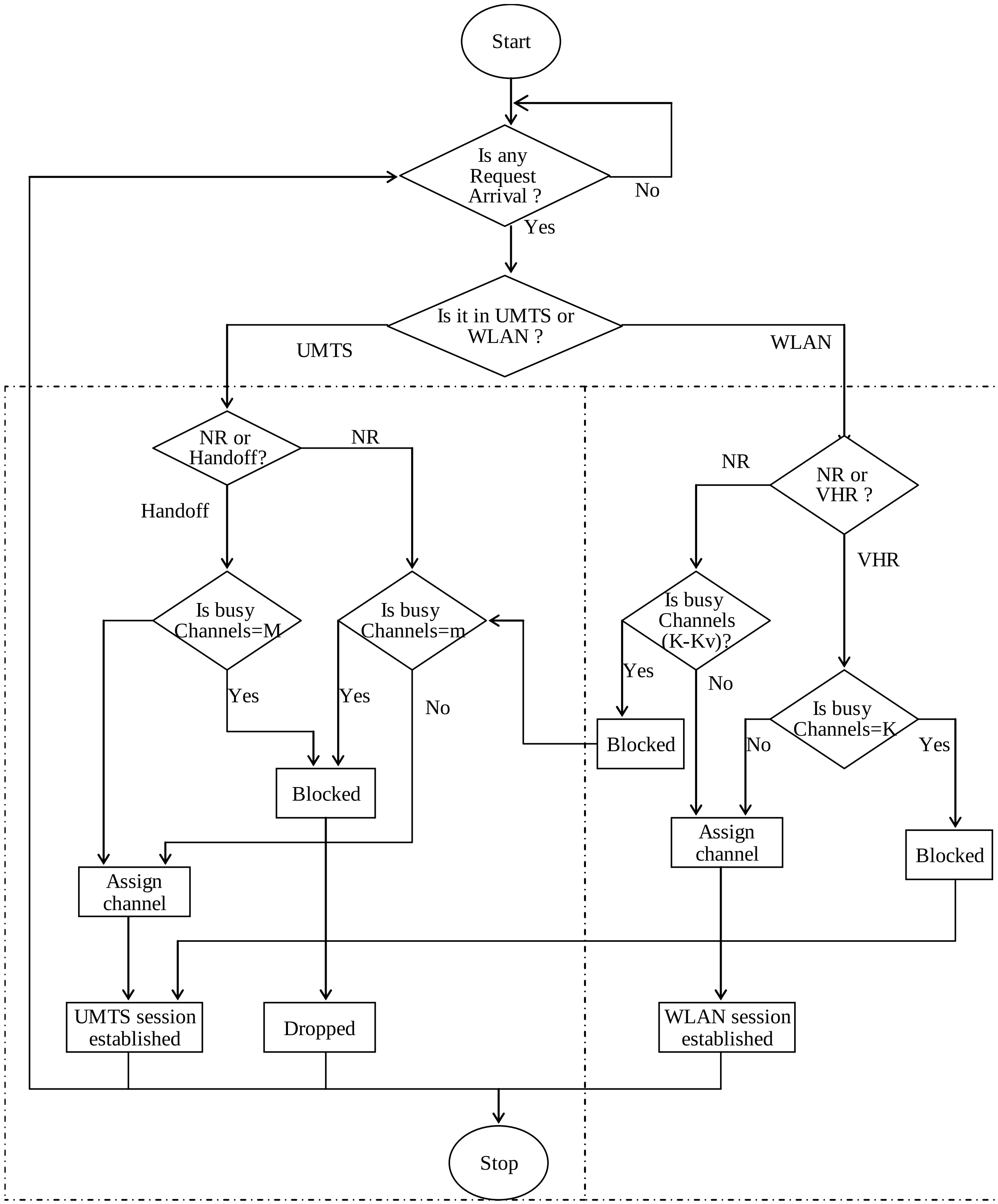


Figure 4. Flow chart for CAC scheme in mixed cell.

IV. State Transition Probabilities

The session mobility scenarios (Section III B) have been represented using states of reqeusts (Section II C). This helps estimation of traffic loads of new and handoff traffic which is given in Section V. Figure 5 presents the state transition scenarios for back-up and hotspot users.

For back-up users: From session mobility scenarios, we see that there are three types of requests from backup users; NR, HHR and VHR. So, there will be three types of *arrival* states*; NR arrival*, *HHR arrival and VHR arrival*. Figure 5 shows that non-blocked NR, HHR and VHR reach to *NR successful*, *HHR successful* and *VHR successful* states, respectively. Each *successful* state can transit to any one of the three states as shown in Figure 3. The *successful* states of NR, VHR and HHR may transit to *HHR arrival* state in neighbor cells and gernerate HHR. They may also transit to *VHR arrival* state generating VHRs in WLAN. The *HHR arrival* and *VHR arrival* inctroduces new *arrival*s. The blocked requests are necessarily dropped.

For hotspot user: There are two types of requests from *hotspot users*: NR and VHR. So, there are two types of arrival states in WLAN; *NR arrival* and *VHR arriva.* Non-blocked *NR arrival* and *VHR arrival* can move to their *successful* states. Each successful sate can move to *VHR arrival* in UMTS-only coverage. A new blcoked-request alternatively initiates NR in UMTS. So, *blocked* state in WLAN transits to *NR arrival* in UMTS. A blocked-VHR in WLAN maintaines the UMTS session. So. Its *blocked* state transits to *completion* state or to *HHR arrival* state in UMTS.

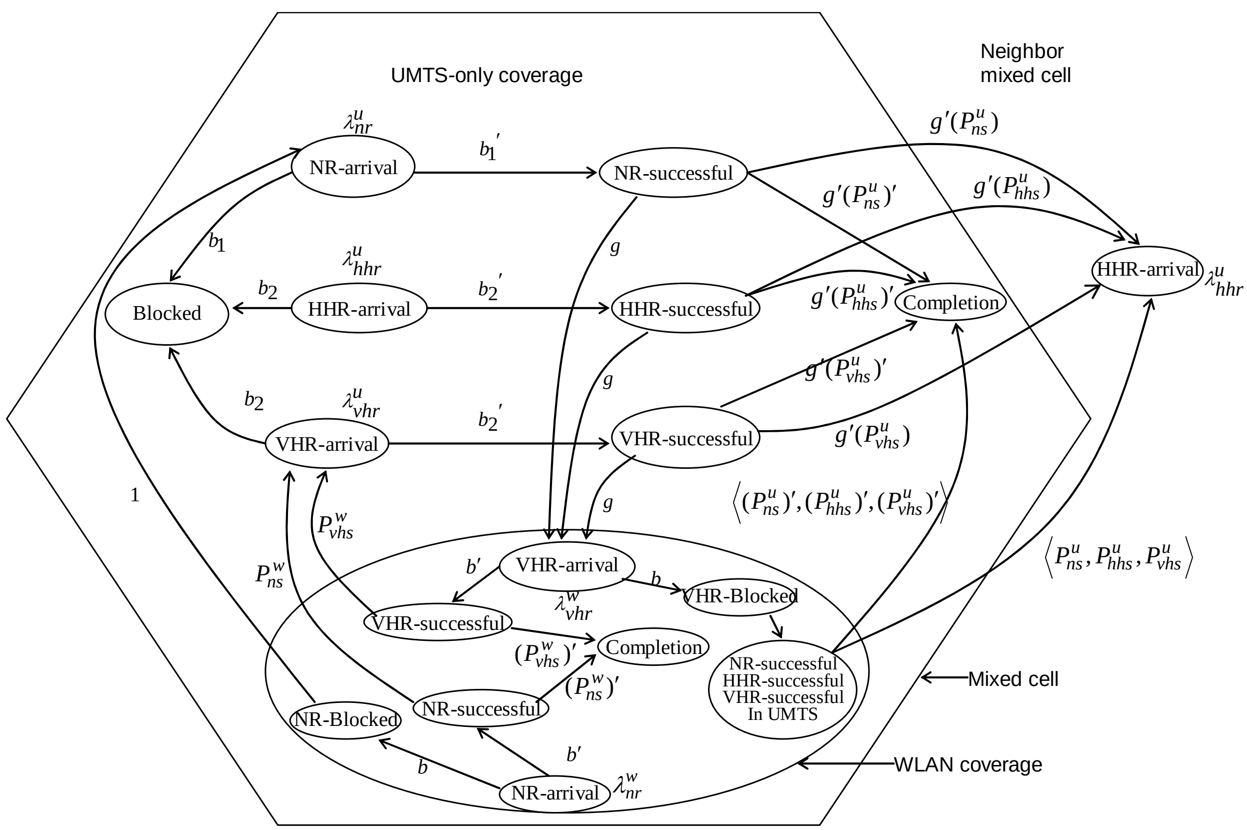


Figure 5. Session mobility scenarios of mixed users represented by state diagram with the transitioin probability from each state.

b_1 -Probability that an NR is blocked on its arrival in UMTS-only coverage. So, it is the probability that an *NR arrival* state transits to *blcoked* state.

b_2 -Probability that an HHR or a VHR is blocked on its arrival in in UMTS-only coverage. So, it is the probability that an *HHR arrival* state transits to *blcoked* state.

b_1' -Transition probability from *NR arrival* to *NR successful* state. $b_1' = (1 - b_1)$.

b_2' -Transition probability from *HHR arrival* to *HHR successful* state. $b_2' = (1 - b_2)$. It is also the transition probability from *VHR arrival* to VHR successful.

g - It is the probability that a data session moves from UMTS-only coverage to WLAN coverage in a mixed cell (Section IIIA). This gives the transition probabilities from *NR successful* or *HHR successful*, or *VHR successful* in UMTS to *VHR arrival* in WLAN.

g' -Probability that a data session of a backup user will not enter WLAN. $g' = (1 - g)$.

P_{ns}^u - Probability that an NS moves from a pure UMTS cell to neighbor UMTS cell and initiates HHR.

P_{hhs}^u -Probability that an HHS moves from a pure UMTS cell to neighbor UMTS cell and initiates HHR. $P_{hhs}^u = (r^u)^{-1} h^u P_{ns}^u - 1$.

P_{vhs}^u -Probability that a VHS moves from a pure UMTS cell to neighbor UMTS cell and the MS initiatres HHR. $P_{vhs}^u = (r^u)^{-1} h^u P_{ns}^u - 1$.

P_{ns}^u, P_{hhs}^u and P_{vhs}^u can be expressed in terms of r^u and h^u. Derivations are given in APPENDIX II.

$g'P_{ns}^u$ - Transition probability from *NR successful* to *HHR arrival (*in neighbor cell).

$g'P_{hhs}^u$ - Transition probability from *HHR successful* to *HHR arrival* (in neighbor cell).

$g'P_{vhs}^u$ - Transition probability from *VHR successful* to *HHR arrival* (in neighbor cell).

Assume b is the blocking probability of any request in WLAN. P_{ns}^w and P_{vhs}^w are the probabilities and an NS and a VHS initiate VHR in UMTS-only coverage, respectively. We can state the transsition probabilites as follows.

b - It is the blocking probability of any request in WLAN. So, it is the probability that an *NR arrival* in WLAN transits to *blcoked* state or a *VHR arrival* in WLAN transits to *blocked* state.

All blocked NRs in WLAN initiates NRs in UMTS. So, transition probability from *NR blocked* (in WLAN) to *NR arrival* (in UMTS) is 1. All blocked VHRs in WLAN are in *successful* states in UMTS i.e., *NR successful*, *HHR successful* and *VHR successful*. So, these states will transit to HHR arrival in neighbor UMTS with the probabilities $g'P_{ns}^u$, $g'P_{hhs}^u$ and $g'P_{vhs}^u$, respectively, which are represented by $\{g'P_{ns}^u, g'P_{hhs}^u, g'P_{vhs}^u\}$. These states will transit to completion in UMTS with probabilities $g'(P_{ns}^u)'$, $g'(P_{hhs}^u)'$ and $g'(P_{vhs}^u)'$, respectively, which are represented by $\{g'(P_{ns}^u)', g'(P_{hhs}^u)', g'(P_{vhs}^u)'\}$.

b' -Transion probability from *NR arrival* to *NR successful*. $b' = (1 - b)$. Since all requests are handled with equal priority, this is also the transion probability from *VHR arrival* to *VHR successful* in WLAN.

P_{ns}^w - Transtion probability from *NR successful* to *VHR arrival*.

P_{vhs}^w - Transition probability from *VHR successful* to *VHR arrival*.

$(P_{ns}^w)'$ - Transition probability from *NR successful* to *completion*.

$(P_{vhs}^w)'$ -Transition probability from VHR *successful* to *completion*.

P_{ns}^w and P_{vhs}^w can be expressend in terms of r^w and h^w. Derivations are given in APPENDIX II.

V. TRAFFIC ESTIMATION AND STEADY STATE PROBABILITY

A. *Traffic estimation*

The transition probability from one state to any other state is given by the product of the probabilities of transitions that take place from that state to other state. Probabilities that *NR arrival*, *HHR arrival* and *VHR arrival* in UMTS generate *HHR arrival* in neighbor are $(1-b_1)(1-g(1-b))P^u_{ns}$, $(1-b_1)(1-g(1-b))P^u_{hhs}$ and $(1-b_2)(1-g(1-b))P^u_{vhs}$, respectively. Probabilities that *NR arrival*, *HHR arrival* and *VHR arrival* in UMTS generate *VHR arrival* in WLAN are $b_1' g$, $b_2' g$ and $b_2' g$, respectively. We assume that λ^u_{nr}, λ^u_{hhr} and λ^u_{vhr} represent the NR, HHR and VHR arrival rates , respectively, in UMTS under steady state conditions. The VHR and NR arrival rates in WLAN are λ^w_{vhr} and λ^w_{nr-hp}, respectively. λ^u_{hhr}, λ^u_{vhr} and λ^w_{vhr} are generated from λ^u_{nr} and λ^w_{nr-hp} due to mobility of the users. . λ^u_{hhr}, λ^u_{vhr} and λ^w_{vhr} are unknown parameters and λ^u_{nr} and λ^w_{nr-hp} are known parameters. We estimate λ^u_{hhr}, λ^u_{vhr} and λ^w_{vhr} in terms of λ^u_{nr} and λ^w_{nr-hp}.

HHR Arrival Rate in UMTS-only Coverage from Backup Users: Writing the flow balance equation under equilibrium state (i.e., *flow in=flow out* across UMTS cells), we write the following.

$$\lambda^u_{hhr} = \lambda^u_{nr-bu}(1-b_1)(1-g(1-b))P^u_{ns} + \lambda^u_{hhr}(1-b_2)(1-g(1-b))P^u_{hhs} + \lambda^u_{vhr}(1-b_2)(1-g(1-b))P^u_{vhs}$$

$$\lambda^u_{hhr} = K_1\lambda^u_{nr} + K_2\lambda^u_{vhr} \tag{5}$$

where $$K_1 = \frac{(1-b_1)(1-g(1-b))P^u_{ns}}{1-(1-b_2)(1-g(1-b))P^u_{hhs}} \tag{6}$$

$$K_2 = \frac{(1-b_2)(1-g(1-b))P^u_{vhs}}{1-(1-b_2)(1-g(1-b))P^u_{hhs}} \tag{7}$$

From equation (5) it is seen that if $K_1 > 1$, the HHR arrival rate is more than NR arrival rate in UMTS-only coverage which is probably unrealistic. Similarly, for $K_2 > 1$, all VHRs will initiate HHRs in UMTS-only coverage which is also bit unrealistic. We neglect such unrealistic situations. Therefore, K_1 and K_2 are assumed to be less than unity such that HHR and VHR arrival rates are always less than NR arrival rate in UMTS-only coverage. Taking derivatives of equations (6) and (7), we have,

$$\frac{dK_1}{dg} = \frac{-(1-b_1)(1-b)P^u_{ns}}{\left(1-(1-b_2)(1-g(1-b))P^u_{hhs}\right)^2} \tag{8}$$

$$\frac{dK_2}{dg} = \frac{-(1-b_2)(1-b)P^u_{vhs}}{\left(1-(1-b_2)(1-g(1-b))P^u_{hhs}\right)^2} \tag{9}$$

b_1, b_2, b, P^u_{ns}, P^u_{hhs}, P^u_{vhs}, g have positive values which are less than unity. Therefore, both K_1 and K_2 decrease with increasing g. From equation (5), we find that HHR arrival rate in the UMTS system decreases with increasing g. Therefore, *in a UMTS cell with embedded WLAN hotspots, the HHR arrival rate in UMTS always decreases with increasing WLAN coverage.*

VHR Arrival Rate in WLAN: From Figure 5, the following can be written.

$$\lambda^w_{vhr} = \lambda^u_{nr-bu}(1-b_1)g + \lambda^u_{hhr}(1-b_2)g + \lambda^u_{vhr}(1-b_2)g \tag{10}$$

VHR Arrival Rate in UMTS-only Coverage: From Figure 5 we can write the following.

$b'P_{ns}^{w}$ - It is the probability that an *NR arrival* state in WLAN reaches to *VHR arrival* state in UMTS-only coverage.

$b'P_{vhs}^{w}$ - It is the probability that a *VHR arrival* state in WLAN will reach to *VHR arrival* state in UMTS-only coverage.

So, VHR arrival rate in UMTS-only coverage is obtained as follows.

$$\lambda_{vhr}^{u} = \lambda_{nr-hp}^{w}(1-b)P_{ns}^{w} + \lambda_{vhr}^{w}(1-b)P_{vhs}^{w} \quad (11)$$

Solving equations (5), (10) and (11), we have the following.

$$\lambda_{vhr}^{u} = K_3 \lambda_{nr-t}^{u} \quad (12)$$

Detailed derivation is given in PPENDIX III.

$$K_3 = \frac{\left(b'P_{ns}^{w} g + b'g\left((r^{w})^{-1} h^{w} P_{ns}^{w} - 1\right)\left(b_1{}' + b_2{}' K_1\right)\left(g' + bg\right)\right)p}{1 - b'b_2{}' g\left((r^{u})^{-1} h^{u} P_{ns}^{u} - 1\right)\left(1 + K_2\right)} \quad (13)$$

λ_{nr-t}^{m} is request arrival rate from total users, and p is the fraction of mixed users out of total users in a mixed cell which can be obtained from the data base of subscription profiles of all users maintained by an operator.

It is verified that K_3 increases with increasing g while other parameters remain constant. Therefore, from equation (12), we find that VHR arrival rate in UMTS system increases with increasing *coverage probability* of WLAN hotspots. This arises from the fact that larger WLAN hotspots coverage shares larger mixed users. So, HHR decreases in UMTS system. But, users are also expected to initiate VHR from WLAN to UMTS. From equations (5), (12), the total HHR arrival rate from mixed users is derived as,

$$\lambda_{hhr}^{u} = K_1 \lambda_{nr-bu}^{u} + K_2 K_4 \lambda_{nr-t}^{u} \quad (14)$$

$$\lambda_{hhr}^{u} = \left((1-g)pK_1 + K_2 K_4\right)\lambda_{nr-t}^{u} \quad (15)$$

HHR Arrival Rate from UMTS-only Users: In Figure 5, $\lambda_{umts-only}^{u}$ and $\lambda_{hhr-umts-only}^{u}$ are the arrival rates of NR and HHR from UMTS-only users. HHR arrival rate is given by the following.

$$\lambda_{hhr-umts-only}^{u} = b_1{}' P_{nds}^{u} \lambda_{umts-only}^{u} + b_2{}' P_{hhds}^{u} \lambda_{hhr-umts-only}^{u} \quad (16)$$

$$\lambda_{hhr-umts-only}^{u} = K_4 \lambda_{nr-t}^{u} \quad (17)$$

where, $\lambda_{umts-only}^{u} = (1-p)\lambda_{nr-t}^{u}$ and $K_4 = \dfrac{b_1{}' P_{nds}^{u}}{1 - b_2{}'\left((r^{u})^{-1} h^{u} P_{nds}^{u} - 1\right)}$

From equations (15) and (17), total HHR arrival rate in UMTS-only coverage is as follows,

$$\lambda_{hhr}^{u} + \lambda_{hhr-umts-only}^{u} = \left((1-g)pK_1 + (1+K_2)K_4\right)\lambda_{nr-t}^{u} \quad (18)$$

B. Steady Probabilities of Sessions

Estimation of blocking probability of a request is mandatory to estimate a dropping probability. A request cannot be granted a channel if all channels are busy, i.e., a request is blocked if all channels in a cell are busy. So, the blocking probability is equal to the steady state probability when all channels are busy. Each cell can be modeled as M/G/m queuing system in which the data channels assigned a base station (i.e., Node B in UMTS) are the servers. Here, the M/G/m queuing system incorporates a loss model in the sense that any arrival, that finds all servers (channels) busy, does not enter a queue, and is lost to the system.

There are three events in UMTS, namely *NR arrival*, *HHR arrival*, *VHR arrival*. Using Erlang loss formula for three dimensional steady state Markov chain the probability that there is *i NR successful*, *j HHR successful* and *k VHR successful* states in a UMTS cell is given as follows.

$$P^{u}(i,j,k) = P^{u}(0,0,0)\left\{\frac{\left(\lambda_{nr}^{u} T_{ns}^{u}\right)^{i}\left(\lambda_{hhr}^{u} T_{vhs}^{u}\right)^{j}\left(\lambda_{vhr}^{u} T_{vhs}^{u}\right)^{k}}{i!\,j!\,k!}\right\} \quad (19)$$

$P(0,0,0)$ is the probability that no request is being processed in a UMTS cell. T_{ns}^{u}, T_{hhs}^{u} and T_{vhs}^{u} are the mean channel holding times (CHTs) in seconds by NSs, HHSs and VHSs, respectively, in a UMTS cell.

$$P^u(0,0,0)=\left[\sum_{i=0}^{m}\frac{\left(\lambda^u_{nr}T^u_{ns}\right)^i}{i!}\left\{\sum_{j=0}^{M-i}\frac{\left(\lambda^u_{hhr}T^u_{hhs}\right)^j}{j!}\left(\sum_{k=0}^{M-i-j}\frac{\left(\lambda^u_{vhr}T^u_{vhs}\right)^k}{k!}\right)\right\}\right]^{-1} \tag{20}$$

From [22], we write, $T^u_{nds}=\frac{1}{h^u}-\frac{r^u}{(h^u)^2}\left(1-f^*_{R^u}(h^u)\right)$, $T^u_{hhds}=T^u_{vhds}=\frac{1}{h^u}\left(1-f^*_{R^u}(h^u)\right)$

$$T^u_{hhs}=T^u_{vhs}=\frac{1}{r^u}\left(1-h^uT^u_{ns}\right)$$

VI. Performance Analysis

A. Blocking Probabilities in UMTS

Blocking of an NR: An NR may be blocked in two cases.

*Case 1: A*n NR is blocked when there are already m ongoing NSs (i.e., *NR successful* states) in a cell. In this case, $i=m$, $j\le(M-m)$ and $k\le(M-m-j)$. In this case, $(j+k)\le(M-m)$ and $(i+j+k)\le M$. From equation (19), the probability that there are m ongoing NDSs in a UMTS cell , i.e., b_1^m is given by,

$$b_1^m=\sum_{j=0}^{M-m}\sum_{k=0}^{M-m-j}P^u(m,j,k)=P^u(0,0,0)\left[\frac{(\lambda^u_{nr}T^u_{ns})^m}{m!}\right]\left[\sum_{j=0}^{M-m}\frac{(\lambda^u_{hhr}T^u_{hhs})^j}{j!}\left\{\sum_{k=0}^{M-m-j}\frac{(\lambda^u_{vhr}T^u_{vhs})^k}{k!}\right\}\right] \tag{21}$$

Case 2: An NR may be blocked when $i<m$ and $j>(M-m)$. In this case, some unreserved channels are not used by NRs, but these may be occupied by HRs which could not be assigned reserved channels The probability of the state with $i=m$ and $j=(M-m)$ is already considered in equation (21) in *case 1*. An NR is blocked when there are total M ongoing data sessions in a cell. All possible states, that there will be M data sessions, and $i<m$ and $j>(M-m)$, are specified by varying i from 0 to $m-1$, j from 0 to $(M-i)$ for each i and $k=(M-m-j)$ for each j. In this case $(i+j+k)=M$ The sum of probabilities of all these states will give the probability that there will M ongoing data sessions. Let b_1^M represent the probability that all M channels are occupied in a UMTS cell.

$$b_1^M=\sum_{i=0}^{m}\sum_{j=0}^{M-i}P(i,j,M-i-j)=P^u(0,0,0)\sum_{i=0}^{m-1}\left[\frac{(\lambda^u_{nr}T^u_{ns})^i}{i!}\left\{\sum_{j=0}^{M-i}\left(\frac{(\lambda^u_{hhr}T^u_{hhs})^j}{j!}\right)\left(\frac{(\lambda^u_{vhr}T^u_{vhs})^{M-i-j}}{(M-i-j)!}\right)\right\}\right] \tag{22}$$

Net blocking probability of an NR in a UMTS cell is $b_1=(b_1^m+b_1^M)$.

$$b_1=P^u(0,0,0)\left\{\begin{array}{l}\left[\frac{(\lambda^u_{nr}T^u_{ns})^m}{m!}\right]\left[\sum_{j=0}^{M-m}\frac{(\lambda^u_{hhr}T^u_{hhs})^j}{j!}\left\{\sum_{k=0}^{M-m-j}\frac{(\lambda^u_{vhr}T^u_{vhs})^k}{k!}\right\}\right]+\\ \sum_{i=0}^{m-1}\left[\frac{(\lambda^u_{nr}T^u_{ns})^i}{i!}\left\{\sum_{j=0}^{M-i}\left(\frac{(\lambda^u_{hhr}T^u_{hhs})^j}{j!}\right)\left(\frac{(\lambda^u_{vhr}T^u_{vhs})^{M-i-j}}{(M-i-j)!}\right)\right\}\right]\end{array}\right\} \tag{23}$$

For an HR: An HR is blocked when there are M ongoing data sessions. In this case, $(j+k)\ge(M-m)$ and $i+j+k=M$. If there are i ongoing NDSs in a UMTS cell, $j=(M-i)$. i will vary from 0 to m and j will be $(M-i)$ for each value of i. So, blocking probability of an HHR or a VHR in the UMTS system is as follows.

$$b_2=\sum_{i=0}^{m}\sum_{j=0}^{m=i}P^u(i,j,M-i-j)=P^u(0,0,0)\sum_{i=0}^{m}\left[\frac{(\lambda^u_{nr}T^u_{ns})^i}{i!}\left\{\sum_{j=0}^{M-i}\left(\frac{(\lambda^u_{hhr}T^u_{hhs})^j}{j!}\right)\left(\frac{(\lambda^u_{vhr}T^u_{vhs})^{M-i-j}}{(M-i-j)!}\right)\right\}\right] \tag{24}$$

Since HHRs and VHRs are handled with equal priority, b_2 is the blocking probability of HHRs as well as VHRs.

B. Blocking Probability in WLAN

There are two events in WALN, *NR arrival* and *VHR arrival*. Blocking of an NR or a VHR in WLAN occurs when all WLAN channels are busy. Using Erlang loss formula for two dimensional steady state Markov chain the probability that there will be *i NR successful* and *k VHR successful* states in WLAN is given as follows.

$$P^w(i,k) = P^w(0,0)\left\{\frac{\left(\lambda^w_{nr-hp}T^w_{ns}\right)^i\left(\lambda^w_{vhr}T^w_{vhs}\right)^k}{i!k!}\right\} \tag{25}$$

$P^w(0,0)$ is the probability that no request is being processed in a WLAN. T^w_{ns} and T^w_{vhs} are the mean CHT in seconds by NSs and VHSs, respectively, in WLAN.

$$P^w(0,0) = \left[\sum_{i=0}^{K}\frac{\left(\lambda^w_{nr-hp}T^w_{ns}\right)^i}{i!}\left\{\sum_{k=0}^{K-i}\frac{\left(\lambda^w_{vhr}T^w_{vhs}\right)^k}{k!}\right\}\right]^{-1} \tag{26}$$

From [22], we write, $T^w_{nds} = \frac{1}{h^w} - \frac{r^w}{(h^w)^2}\left(1 - f^*_{R^w}(h^w)\right)$, $T^u_{vhds} = \frac{1}{h^w}\left(1 - f^*_{R^w}(h^w)\right)$

Blocking probability in WLAN is equivalent to the probability that all channels are occupied by NRs and VHRs.

$$b = \sum_{i=0}^{K}P^w(i,K-i) = P^w(0,0)\left[\sum_{i=0}^{K}\left(\frac{(\lambda^w_{nr-hp}T^w_{ns})^i(\lambda^w_{vhr}T^w_{vhs})^{K-i}}{i!(K-i)!}\right)\right] \tag{27}$$

C. Dropping Probability in a Mixed Cell

For simplicity we assume all users in mixed cell are mixed users, i.e., $p=1$.

Dropping Probability of NR: In a mixed cell, from equations (xiv) and (xv) in APPENDIX, $\lambda^u_{nr-bu} = g\lambda^m_{nr-t}$ and $\lambda^w_{nr-hp} = (1-g)\lambda^m_{nr-t}$. So, an NR arrival in UMTS-only coverage of a mixed cell occurs with probability $(1-g)$ i.e. g' and that occurs in the WLAN system with probability g. An NR arrival in the UMTS system is blocked with probability b_1 and that in the WLAN system is b. So, an NR arrival in UMTS-only coverage of mixed cell is blocked with probability $(1-g)b_1$ i.e., $g'b_1$. Since every blocked NR is necessarily dropped in UMTS, $g'b_1$ is the dropping probability of NRs from back-up user. Since a blocked NR in WLAN accesses UMTS, the dropping probability of an NR from hotspot user gbb_1. So, net dropping probability of an NR in an entire mixed cell is the sum of the dropping probabilities of NRs from back-up users and hotspot users i.e., P_{dnr} is given by the following.

$$P_{dnr} = (1-g)b_1 + gbb_1 \tag{28}$$

$$b_1 - P_{dnr} = gb_1(1-b) \tag{29}$$

In equation (29), if $g=0$, then $P_{dnr} = b_1$. This implies that *the dropping probability of NR in a mixed cell without WLAN coverage is equal to that in pure UMTS cell.* In equation (29), if both g and b positive fractions, then $P_{dnr} < b_1$. Therefore, a mixed cell with WLAN hotspots always yield lower dropping probability for NRs. Now consider that blocked requests of hotspot users are not permitted to access UMTS [8], [25]. In that case, the dropping probability of NR is given,

$$b_1 - P_{dnr} = g(b_1 - b) \tag{30}$$

It is seen from equation (29) that dropping probability of an NR in a mixed cell is lower than that in a pure UMTS cell if and only if the blocking probability of an NR in WLAN is less than that in a pure UMTS cell i.e., only if $b < b_1$. Since our CAC scheme, diverts blocked requests of WLAN to UMTS, the net dropping probability of NR is not affected by higher blocking probability of WLAN.

Dropping Probability of HHR: In UMTS-only coverage, an HHR occurs with probability $(1-g)$ i.e., g' [7]. All blocked HHRs are necessarily dropped in UMTS. So, from Figure 5, dropping probability of an HHR, P^{u}_{dhhr} can be written as follows.

$$P_{dhhr} = (1-g)b_2 = g'b_2 \tag{31}$$

In equation (31), $g \neq 0$, then $P_{dhhr} < b_2$. So, *dropping probability of an HHR in a mixed cell is always less than that in a pure UMTS cell.*

Dropping probability of VHR: All blocked VHRs in UMTS are necessarily dropped. But all blocked VHRs in WLAN maintains the UMTS session and are not dropped. From Figure 5, there is only one scenario of dropping of VHRs in a mixed cell i.e., a VHR is dropped in only UMTS. The arrival or VHR in WLAN occurs with probability g . VHR arrival in UMTS occurs under two scenarios; one, when an NDS moves from WLAN to UMTS-only coverage and two, when VHDS moves from WLAN to UMTS. From Figure 5, the probability of occurrence of VHR in UMTS due to moving of an NS from WLAN to UMTS is $gb' P^{w}_{ns}$. Probability that a VHR occurs due to a VHS initiating VHR from WLAN to UMTS is $g(1-b)P^{w}_{vhs}$ i.e., $gb' P^{w}_{vhs}$. So, total probability that a VHR occurs in UMTS is $gb'\left(P^{w}_{vhs} + P^{w}_{ns}\right)$. Each VHR in UMTS-only coverage is blocked with probability b_2. So, the probability dropping of a VHR in UMTS is $b_2 gb'\left(P^{w}_{vhs} + P^{w}_{ns}\right)$.

Thus, dropping probability of a VHR in a mixed cell, P_{dvhr} is the sum of the dropping probability of VHR in WLAN and that in UMTS. So, we can write the following.

$$P_{dvhr} = b_2 gb'\left(P^{w}_{vhs} + P^{w}_{ns}\right) \tag{32}$$

Dropping Probability of HR: Dropping probability of an HR, in a mixed cell, is sum of the dropping probabilities of an HHR and a VHR. Thus, from equations (31) and (32), dropping probability of an HR in a mixed cell is as follows.

$$P_{hr} = (1-g)b_2 + b_2 gb'\left(P^{w}_{vhds} + P^{w}_{nds}\right) \tag{33}$$

$$\text{or, } b_2 - P_{hr} = gb_2\left[1 - b'\left(P^{w}_{vhds} + P^{w}_{nds}\right)\right] \tag{34}$$

From equation (34), if $g = 0$, then $P_{hr} = b_2$. So, *dropping probability of a HR in a mixed cell without WLAN coverage is equal to the dropping probability of a HHR in a pure UMTS cell*. If g , b , b_2 and $\left(P^{w}_{vhds} + P^{w}_{nds}\right)$ are positive fractions, then $P_{hr} < b_2$. Therefore, *dropping probability of a HR in a mixed cell is always less than that in a pure UMTS cell*. We consider a CAC scheme of a mixed cell with tunnel WLANs [8], [25] in which all blocked VHRs are dropped in WLAN. In that case, dropping probability of HRs is given by,

$$b_2 - P_{hr} = g(b_2 - b) - b_2 gb'\left(P^{w}_{vhds} + P^{w}_{nds}\right) \tag{35}$$

If $b < b_2$, then $P_{hr} < b_2$. Therefore, *dropping probability of a HR in a mixed cell is always less than that in a pure UMTS cell if and only if the blocking probability of a request in WLAN is less than that of an HHR in a pure UMTS cell*. However, the CAC scheme in this article, helps blocked VHRs to maintain the ongoing session in UKMTS. Net dropping of HRs is not affected by higher blocking probability of WLAN.

VII. Numerical Results

Our analytical model is validated by the simulation results. We disable the transition of *NR-blocked* and *VHR-blocked* states of WLAN to fit our model to T-WLAN model [8], i.e., blocked requests of WLAN are necessarily dropped. Then we put the values of parameters which are used for simulation model [8]. We use $n = 2$, $n_1 = 3$, $n_2 = 2$, $\alpha_1 = 0.4$, $\alpha_2 = 0.6$, $\theta_1 = 0.0267$ and $\theta_2 = 0.0133$ in equation (3). Then we set $h = 3\,\text{sec}$, $r^{u} = 60\,\text{sec}$, $M = 11$, $m = 0$ for UMTS system. For WLAN, we use $n = 2$, $n_1 = 10$, $n_2 = 1$, $\alpha_1 = 0.1$, $\alpha_2 = 0.9$, $\theta_1 = 0.0197$ and $\theta_2 = 0.0164$ in equation (3) and set $r^{w} = 60\,\text{sec}$ and $b = 0$. We set $d = 11$.

The system capacity (i.e., number of *total users* supported in a mixed cell with limiting blocking probability 0.1) has been normalized with respect to that of a pure UMTS cell. The normalized system capacity increases 8 times with

50% increase in WLAN coverage. The analytical results show an almost exact match with the simulation results given in [8] (Fig. 6).

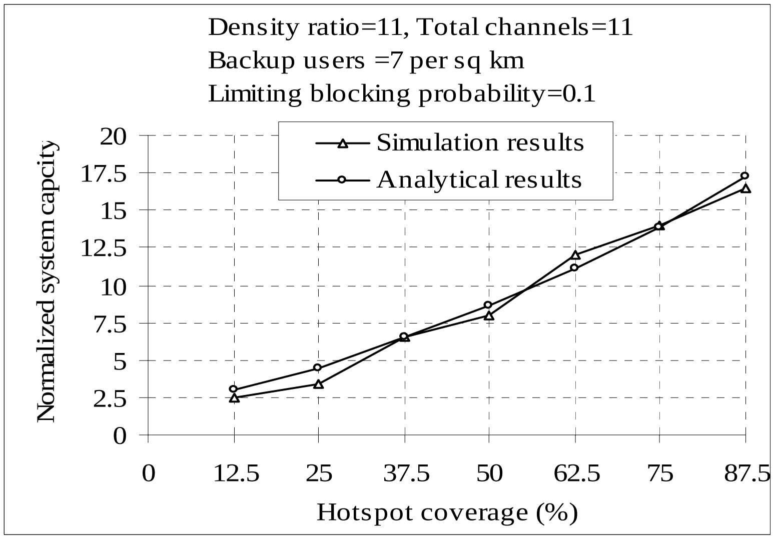


Figure 6: System Capacity Versus hotspot coverage.

We compare the request dropping performance between T-WLAN and proposed access schemes. We use $n = 2$, $n_1 = 3$, $n_2 = 2$, $\alpha_1 = 0.4$, $\alpha_2 = 0.6$, $\theta_1 = 0.45$ and $\theta_2 = 0.35$ in equation (3) and set $h = 2.5$ sec, $r^u = 3.31$ sec, $M = 30$, $m = 5$ for UMTS system. For WLAN, we use $n = 2$, $n_1 = 2$, $n_2 = 2$, $\alpha_1 = 0.2$, $\alpha_2 = 0.8$, $\theta_1 = 0.25$ and $\theta_2 = 0.35$ in equation (3), and set $r^w = 2.75$ sec, $K = 50$ and $d = 1$ for WLAN system. Request arrival rate from mixed users $\lambda_{nc}^m = 14$ per sec. WLAN traffic is increased by increasing the request arrival rate from WLAN users (i.e., users cannot access UMTS). Figure 7(a) shows that dropping probability of NR in a mixed cell remains low as long as blocking probability in the WLAN system is less than that of the UMTS system. This occurs till the request arrival rate of WLAN users is less than 9 (approximately) per second. Beyond the request rate of 10, the dropping probability of an NR in a mixed cell is more than that of a pure UMTS cell. Figure 7(b) shows that the blocking probability of WLAN exceeds that of the UMTS system, but dropping probability of NR in a mixed cell never exceeds that of the UMTS system. This is due to the fact that all blocked WLAN requests are transferred to UMTS, thereby decreasing the dropping probability.

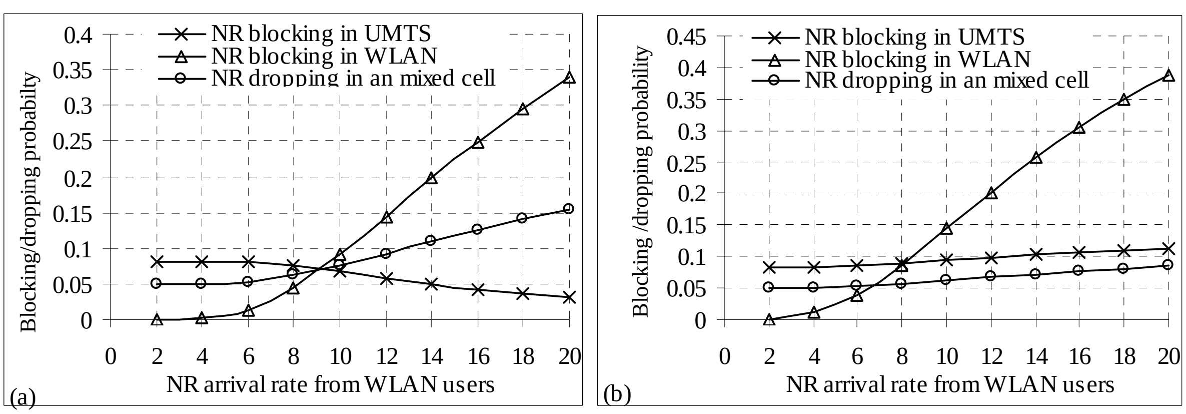


Figure 7: Blocking/dropping probability of NR with increasing new traffic (a) T-WLAN model and (b) improved WLAN-first scheme (proposed model).

Figure 8 shows the change in dropping probability of NR in a mixed cell with increasing new traffic with the effect of g. As g increases this dropping probability decreases. At NR arrival rate of 14 per sec and $g = 0.40$, the dropping probability decreases by 67.4% with respect to a pure UMTS cell (i.e., $g = 0$). To provide this performance level the UMTS-first access scheme [7] needs at least 10 reserved WLAN channels. Our scheme additionally permits NRs to access WLAN and supports session-handover from UMTS to WLAN, its request dropping performance is quite comparable with UMTS-first scheme without reserving WLAN bandwidth for handoff handling. Similar performance is obtained for handoff dropping also which is not provided due to limited scope.

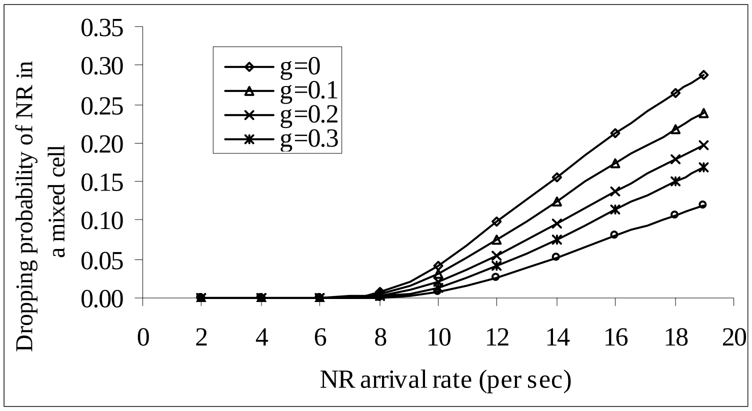


Figure 8: Dropping probability of NR in a mixed cell with increasing new traffic

VIII. CONCLUSION

WLAN-first access scheme supports handover of ongoing session between UMTS and WLAN. The results of system capacity are useful to quantify the requisite WLAN coverage to maintain threshold blocking performance of a UMTS cell The proposed under increasing traffic load. Model provides the effect of both WLAN and UMTS traffic on the dropping probability of a request. It mitigates the effect of increasing WLAN traffic on request dropping probability by transferring the blocked request of WLAN towards to UMTS system.

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APPENDIX I. $g \approx \dfrac{1}{[Ad]^{-1}+1}$

Proof: From notation of system parameters, $A = \dfrac{A^w}{A^u}$; where A^w and A^u are the coverage of all WLAN hotspots in a mixed cell and coverage of a pure UMTS cell, respectively. $A << 1$.

$$A^w = AA^u \tag{i}$$

$$d = \frac{\text{hotspot users per unit area of WLAN coverage}}{\text{backup users per unit area of WLAN coverage}}$$

$$\text{or, } d = \frac{\dfrac{\text{hotspot users}}{\mathrm{AA^u}}}{\dfrac{\text{backup users}}{(\mathrm{A^w - AA^u})}} = \frac{(1-A)}{A}.\frac{\text{hotspot users}}{\text{backup users}} = \left(\frac{1}{A}-1\right)\frac{\text{hotspot users}}{\text{backup users}}$$

$$\text{since} \quad A << 1, \; \frac{1}{A} >> 1 .$$

$$\text{So, } d = \left(\frac{1}{A}\right)\frac{\text{hotspot users}}{\text{backup users}} \text{ or, backup users} \approx [\text{Ad}]^{-1}(\text{hotspot users}) \tag{ii}$$

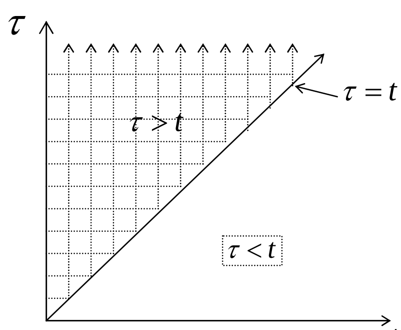
From the definition of g we write,

$$g = \frac{\text{hotspot users}}{\text{mixed users}} = \frac{\text{hotspot users}}{\text{hotspot users} + \text{backup users}} \tag{iii}$$

From equations (ii) and (iii) we get, $\qquad g \approx \dfrac{1}{1+[\text{Ad}]^{-1}}$

APENDIX II. $P_{nds}^{u} = \dfrac{r^{G}\left(1 - f_{R^{G}}^{*}(h^{G})\right)}{h^{G}}$

P_{nds}^{u} - This is the probability that an NDS in UMTS initiates HHR in a neighbor UMTS cell. An NDS will initiate HHR if the session holding time (SHT) is greater than the residual cell residence time (CRT). So, the probability of HHR is given by the probability that the SHT is greater than the residual CRT, i.e., $P_{nds}^{u} = P(H^{u} > R_{r}^{u})$. Shaded area of Figure i. shows the event space given by the condition $H^{u} > R_{r}^{u}$. This gives the range of integration of *pdf*s of H^{u} and R_{r}^{u}. Replacing H^{u} by τ and R_{r}^{u} by t, we can write the following.



$$P_{nds}^{u} = P(H^{u} > R_{r}^{u}) = P(\tau > t)$$

So, P_{nds}^{u} is given by the joint probability under shaded area in Figure i.

$$P_{nds}^{u} = \int_{0}^{\infty}\int_{t}^{\infty} f_{R_{r}^{u}}(t) f_{H^{u}}(\tau) d\tau dt \tag{3.17}$$

Under the consideration of exponential distribution of H^{u}, we can write:

$$f_{H^{u}}(\tau) = h^{u} e^{-h^{u}\tau} \tag{3.18}$$

Using residual life theorem of random variable [195], we can write:

$$f_{R_{r}^{u}}(t) = r^{u}\left(1 - F_{R^{u}}(t)\right) \tag{3.19}$$

From equations (3.17), (3.18) and (3.19), we get

$$P_{nds}^{u} = \int_{0}^{\infty}\int_{t}^{\infty} r^{G}\left(1 - F_{R^{u}}(t)\right)\left(h^{u} e^{-h^{u}\tau}\right) d\tau dt$$

$$= r^{u}\left\{\int_{0}^{\infty}\left(1-\int_{0}^{t} f_{R^{u}}(t)dt\right)e^{-h^{u}t}dt\right\};$$

where, $F_{R^{u}}(t) = \int_{0}^{t} f_{R^{u}}(t)dt$.

$$P_{nds}^{u} = r^{u}\left\{\int_{0}^{\infty} e^{-h^{u}t}dt - \int_{0}^{\infty}\left(\int_{0}^{t} f_{R^{u}}(t)dt\right)e^{-h^{u}t}dt\right\}$$

Using integration property of Laplace transform [201] with the variable h_G , following can be written.

$$P_{nds}^{u} = r^{u}\left\{\int_{0}^{\infty} e^{-h^{uG}t}dt - \frac{f_{R^{u}}^{*}(h^{u})}{h^{u}}\right\} = \frac{r^{u}\left(1-f_{R^{u}}^{*}(h^{u})\right)}{h^{u}} \qquad (3.20)$$

Similarly, $P_{hhds}^{u} = P(H_{r}^{u} > R^{u}) = P(H^{u} > R^{u})$; since $H_{r}^{u} = H^{u}$ from the memory less property of exponential distribution.. $P_{hhds}^{u} = \int_{R^{u}}^{*}(h^{u})$. So, $P_{hhds}^{u} = (r^{u})^{-1}h^{u}P_{nds}^{u} - 1$ and $P_{vhds}^{u} = P(H^{u} > R^{u}) = \int_{R^{u}}^{*}(h^{u}) = (r^{u})^{-1}h^{u}P_{nds}^{u} - 1$.

Similarly, $P_{nds}^{w} = \dfrac{r^{w}\left(1-f_{R^{u}}^{*}(h^{w})\right)}{h^{w}}$ and $P_{vhds}^{w} = (r^{w})^{-1}h^{w}P_{nds}^{w} - 1$

APPENDIX III. $\lambda_{vhr}^{u} = \dfrac{\left(b'P_{nds}^{w}g + b'P_{vhds}^{w}g\left(b_{1}' + b_{2}'K_{1}\right)g'\right)p}{1-b'P_{vhds}^{w}b_{2}'g(1+K_{2})}\lambda_{nr-t}^{u}$

Proof:

$$\lambda_{hhr}^{u} = K_{1}\lambda_{nr}^{u} + K_{2}\lambda_{vhr}^{u} \qquad \text{(iv)}$$

$$\lambda_{vhr}^{w} = \lambda_{nr}^{u}b_{1}'g + \lambda_{hhr}^{u}b_{2}'g + \lambda_{vhr}^{u}b_{2}'g \qquad \text{(v)}$$

$$\lambda_{vhr}^{u} = \lambda_{nr-hp}^{w}b'P_{nds}^{w} + \lambda_{vhr}^{w}b'P_{vhds}^{w} \qquad \text{(vi)}$$

Applying equation (iv) in equation (v), we have,

$$\lambda_{vhr}^{u} = b'P_{nds}^{w}\lambda_{nr-hp}^{w} + b'P_{vhds}^{w}b_{1}'g\lambda_{nr-bu}^{u} + b'P_{vhds}^{w}b_{2}'g\lambda_{hhr}^{u} + b'P_{vhds}^{w}b_{2}'g\lambda_{vhr}^{u} \qquad \text{(vii)}$$

Applying equation (iv) in (vii), we write the following.

$$\lambda_{vhr}^{u} = b'P_{nds}^{w}\lambda_{nr-hp}^{w} + b'P_{vhds}^{w}b_{1}'g\lambda_{nr}^{u} + b'P_{vhds}^{w}b_{2}'gK_{1}\lambda_{nr}^{u} + b'P_{vhds}^{w}b_{2}'gK_{2}\lambda_{vhr}^{u} + b'P_{vhds}^{w}b_{2}'g\lambda_{vhr}^{u} \quad \text{(viii)}$$

$$\lambda_{vhr}^{u} = \frac{b'P_{nds}^{w}}{1-b'P_{vhds}^{w}b_{2}'g(1+K_{2})}\lambda_{nr-hp}^{w} + \frac{b'P_{vhds}^{w}g\left(b_{1}' + b_{2}'K_{1}\right)}{1-b'P_{vhds}^{w}b_{2}'g(1+K_{2})}\lambda_{nr}^{u} \qquad \text{(ix)}$$

$$p = \frac{\text{mixed users}}{\text{total users}}\text{, or mixed users} = p \times (\text{total users}) \qquad \text{(x)}$$

$$\text{UMTS-only users} = (1-p)(\text{total users}) \qquad \text{(xi)}$$

$$g = \frac{\text{hotspot users}}{\text{mixed users}} \qquad \text{(xii)}$$

From equations (x) and (xi), $gp = \dfrac{\text{hotspot users}}{\text{total users}}$ (xiii)

So, gp is the fraction of hotspot users out of total users in a mixed cell. We assume that request arrival rate from a particular class of users occurs in proportion with number of users. λ_{nr-t}^{m} is NR arrival rate from *total us*ers in a mixed cell.

Request arrival rate from *mixed user* (from equation (x)) = $p\lambda_{nr-t}^{m}$

Request arrival rate from hotspot users (from equation (xii)), $\lambda_{nr-hp}^{w} = gp\lambda_{nr-t}^{m}$ (xiv)

Request arrival rate from backup users, $\lambda_{nr-bu}^{u} = (1-g)p\lambda_{nr-t}^{m} = g'p\lambda_{nr-t}^{m}$ (xv)

All blocked calls of hotspot users also initiate NRs in UMTS. So, to NR arrival rate, λ_{nr}^{u} is given by,

$$\lambda_{nr}^{u} = \lambda_{nr-bu}^{u} + b\lambda_{nr-hp}^{w} = g'p\lambda_{nr-t}^{m} + bgp\lambda_{nr-t}^{m} \qquad \text{(xvi)}$$

We apply equation (xiv) and (xvi) in equation (ix) and write the following.

$$\lambda_{vhr}^{u} = \frac{b'P_{nds}^{w}gp}{1-b'P_{vhds}^{w}b_2{}'g(1+K_2)}\lambda_{nr-t}^{m} + \frac{b'P_{vhds}^{w}g\left(b_1{}' + b_2{}'K_1\right)(g'+bg)p}{1-b'P_{vhds}^{w}b_2{}'g(1+K_2)}\lambda_{nr-t}^{m}$$

$$\lambda_{vhr}^{u} = K_3\lambda_{nr-t}^{m}$$

$$K_3 = \frac{\left(b'P_{nds}^{w}g + b'g\left((r^{w})^{-1}h^{w}P_{nds}^{w} - 1\right)\left(b_1{}' + b_2{}'K_1\right)(g'+bg)\right)p}{1-b'b_2{}'g\left((r^{u})^{-1}h^{u}P_{nds}^{u} - 1\right)(1+K_2)}$$