Enhancing the Modelling of Vertical Handover in Integrated Cellular/WLAN Environments

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***Abstract*—This paper presents a new analytical model to enhance the modelling of vertical handover for integrated cellular/WLAN systems. The WLAN system considered is within the coverage area of cellular network, hence users can have a downward vertical handover to the WLAN and/or an upward vertical handover to the cellular network. Recent work on the modelling of these systems using a two-stage model with feedback encountered some complications in terms of handling certain streams. The possibility of having continuous streams which keep on switching between WLAN and cellular systems, may reduce the practicality of the models. The new analytical model presented in this paper restricts certain flows to make sure that the handover calls from the WLAN to the cellular system are not allowed back to the WLAN. Previously proposed analytical models, which do not nullify these streams may not reflect real systems and the results obtained may not be practically applicable especially for such a configuration of cellular/WLAN interaction. A new model is presented with an extra random variable in order to ensure that Markovian property is not violated. Results are presented to show that the new model is a significant improvement but more work is needed to analyse more complex scenarios.**

***Index Terms*—Vertical Handover, Integrated Wireless Networks, Quality-of-Service, New Performance Models**

I. INTRODUCTION

The integration of different wireless technologies has attracted much attention from both academia and industry. The integration of 3G cellular networks and WLANs have become a very active area in the development of the next generation wireless networks. WLANs can offer high-speed data connections in a small coverage with relatively low cost. On the other hand, cellular networks are core networks and have a fixed infrastructure. Cellular networks have much larger coverage area (several kilometres) but with relatively low data rates. Taking advantages of both networks is beneficial to both service providers and users. The limitations of individual wireless access networks due to finite coverage areas are being overcome by the integration of different technologies using vertical handover techniques [15]. In this environment, where a network, say *A*, is completely covered by network *B*, then if we make a handover from network *A* to network *B*, this is referred to as an *upward vertical handover* because we are going from a smaller network with substantial bandwidth to a network of a much larger coverage with lower bandwidth. While a handover from network *B* to network *A* is referred to as a *downward vertical handover* because we are going from a larger to a smaller network [7], [9], [15].

This poses many challenges such as decision making on the best time to handover, selecting the best network and reducing handover latency and packet loss [5], [8], [9], [13]. In addition, mobile devices and wireless environments exhibit limitations in terms of memory capacity and processing power [11]. Hence, the performance modelling of various mobile systems has recently become popular [4], [6], [7], [8], [9], [13], [14]. Unlike traditional algorithms, mobility management systems will need many parameters including, velocity, coverage areas as well as the location of mobile devices and base-stations to support vertical handover related processes [5], [8], [9], [11], [13]. Integrating various technologies is an effective way and currently, WLANs can be considered as a complementary service for integrated systems to improve QoS when it is combined with the wide area benefits of 3G networks. The complexity of these systems is very evident in terms of performance analysis, when existing modelling approaches are considered [4], [5], [6], [7], [8], [9], [10],[13], [14]. Simulation is an efficient tool for studying detailed system behaviour but it becomes costly and complicated in some situations, particularly as the system size increases. On the other hand analytical modelling is also essential to understand the underlying principles. It also has the advantage of incorporating numerical optimization techniques for network design [1]. Hence, research on an analytic model of such a system is still a hot topic. Open queueing network models with finite capacity have been applied in many areas such as telecommunication engineering, wireless and mobile systems etc. [10], [11]. In addition Markov models provide more flexibility and produce numerical results for many interesting performance measures. In this paper, the characteristics of the feedback loops are investigated based on the model presented in [7]. In practical mobile systems, due to different coverage areas for different networks, WLAN networks tend to be totally covered by a cell in a 3G network.

Mobile users may arrive into a 3G cell with a horizontal handover from another 3G network. When a WLAN hotspot is discovered by the mobile user (the mobile user gets into the coverage area of WLAN), a downward vertical handover can be performed to the hotspot. A mobile node within the hotspot, may leave the coverage area and perform a upward vertical handover back to a cellular network. A mobile user which is leaving the coverage area of WLAN due to mobility, is not likely to get back to the coverage area of WLAN. Therefore when the flow of users are being modelled the stream of users arrived to cellular system from the WLAN should not be allowed back to the WLAN since this may cause an infinite loop of transitions between cells. In other words, such a behaviour may be modelled by closed queuing systems rather than open ones. In practice, once there is an upward vertical handover from the WLAN to the cellular system, there is no handover back to the WLAN, hence there is no feedback loop. In order to capture this adequately a model that prevents handover hysteresis between the WLAN and the cellular network is needed. In this paper an improved analytical model approach which differentiates the requests coming from WLAN and requests originated in cellular system for the analysis of integrated 3G cellular network and WLAN is presented. Once these streams are differentiated, the calls in cellular system which are coming from WLAN are not allowed back to WLAN. The rest of the paper is organized as follows: In Section II the model considered is described. In Section III two Markov models are presented in order to show the effects of the feedback loop while modelling vertical handovers. In Section IV and V, two scenarios are considered, and numerical results are presented with emphasis on showing the affects of feedback loops for cellular/WLAN integration. Conclusions and future work are provided in Section VI.

II. Model Description

The proposed model considers the modelling of the integrated cellular/WLAN systems for performance evaluation. Similar modelling approaches are introduced for performance evaluation of integrated 3G cellular network and WLAN systems as a two stage open queuing systems in [1], [5], [7], [8], [9], [10], [13] and [14]. The model presented considers both vertical and horizontal handovers. Since the coverage of a 3G cell is normally much larger than that of a WLAN, it is possible to assume that the WLAN is going to be deployed within the cellular network as shown in Fig. 1. Since the WLAN is within the coverage area of the cellular network, mobile users of the cellular network can switch over to the WLAN once they are in the coverage area, or remain connected to the cellular network. It is assumed that, at a particular time, each user can send one request to only one network for connection [5], [13], [14].

Based on the model presented in [7], the two stage open queuing system for performance evaluation of cellular/WLAN integration is shown in Fig. 2. The system considered is similar to systems considered in previous studies, such as in [7], [13] and [14]. In Fig. 2, W_c and W_w represent the queuing capacities of the cellular and WLAN systems respectively. The system consists of S identical channels in the first stage and a single channel at the second stage. The maximum number of calls in the system is equal to the number of calls assigned

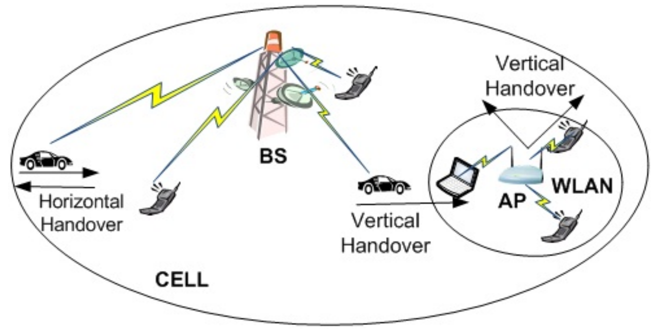

Fig. 1. 3G Cellular/WLAN integration

to the channels plus the queuing capacity, L_c=S+W_c. On the other hand, a single server and a bounded queue with a capacity of W_w are considered at the second stage. This can be expressed as L_w=1+W_w. For analytical tractability, the hexagon cell shape and WLAN coverage area are assumed to be circular with radius of *R* and *r*, respectively. More information about the model can be found in [7].

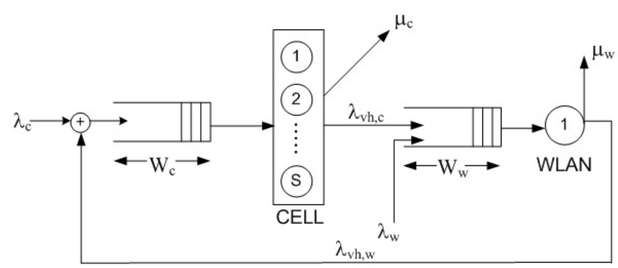

Fig. 2. Two stage open queuing system

In [12], it is shown that the behaviour of the distributed coordination function and the characteristics of CSMA/CA are well approximated and a single channel queuing model could be assumed for WLANs. In addition, in [6], an experimental work is shown. Their analysis and testbed results show that a WLAN system could be modelled as a queuing system with a single queue and a single channel. The arrival rates and service times follow Poisson and exponential distributions. The arrival and service rates are given as λ_c, $\lambda_{vh,c}$, λ_w, $\lambda_{vh,w}$, and μ_c, μ_w for cellular and WLAN respectively. $\lambda_{vh,c}$ and $\lambda_{vh,w}$ represent the rates of serviced calls leaving the system from cellular and WLAN networks respectively. In other words $\lambda_{vh,c}$ and $\lambda_{vh,w}$ are the vertical handover rates of 3G cellular and WLAN respectively. The users in the cellular system may stay in the cell until they get a channel to be served, or if they get into the coverage area of WLAN (due to mobility), they may be allowed to handover to the WLAN system. Integer valued random variables, $I(t)$ and $J(t)$ specify the number of calls present at a time t for the cellular and the WLAN systems respectively.

III. Markov Models for Vertical Handover

Queueing theory and Markov processes are widely used in performance modelling of wireless and mobile communication systems. Markov models are alternative analytical methodologies for the analysis of such systems based on the actual real life system behaviour, leading to both credible and cost-effective approximations for the performance prediction and optimisation of mobile systems. In this paper, continuous time Markov chains (CTMC) are employed to analyse and show the effects of unseen feedback loop for an integrated cellular/WLAN queuing system. All the models demonstrated are irreducible Markov processes. Please note that for simplicity, we consider simple scenarios to analyse the systems. For instance one WLAN originating call is considered for analysis in first scenario. In addition, the model presented in this paper and the model in [7], are considered comparatively for a simple scenario where there are up to two calls in cellular system and a single call in WLAN.

A. The Handover Model

The Markov models used in [7] do not differentiate the requests originated within the cell from the requests coming from WLAN. For such a configuration, two random variables are sufficient and the Markov chains are shown in Fig. 3 and Fig. 6. The number of calls in the cellular network including the one(s) in service is represented using state variable $I(t)$. $J(t)$ is the total number of calls in the WLAN system at time t, including the one(s) in service. Then, $Z = \{[I(t), J(t)]; t \geq 0\}$ is an irreducible Markov process on a lattice strip (a QBD process), that models the system. Once the system is solved for the steady state probabilities $P_{i,j}$, various performance measures can be obtained. In this study, the mean queue length of the cellular system (MQL_c) and the WLAN (MQL_w) are considered respectively which can be obtained as follows:

$$MQL_c = \sum_{i=0}^{L_c} i \sum_{j=0}^{L_w} P_{i,j},\ MQL_w = \sum_{j=0}^{L_w} j \sum_{i=0}^{L_c} P_{i,j}$$

The model is two-dimensional and an exact spectral expansion solution is employed in order to obtain a steady state solution. The details of the exact spectral expansion solution method can be found in [2], [7]. Each call may experience a number of handovers during its connection lifetime in cellular network. However when a WLAN is located inside the coverage area of cellular system, calls are expected to hand over from the WLAN to the cellular network and terminate in the cellular network or have a handover to neighbouring cells. As shown in Fig. 3 and Fig. 6, the systems used in [7] are unable to differentiate between cellular calls originated in the cellular networks from calls that have already gone through the WLAN network. Therefore the system allows calls handed over from WLAN to cellular network to hand over back to the WLAN causing an infinite loop of call requests circulating in the system similar to the behaviour of closed queuing systems.

B. Introducing and Additional Random Variable

The new model presented in this section is able to differentiate the cellular calls originated in cellular systems from the calls coming from the WLAN. An additional state variable is used to be able to differentiate the number of requests originated in cellular network from the ones coming from WLAN. The notation of the new model is accordingly given by the variables (C, C_w, W), where the first variable C, is the number of calls in the cellular system. This can be either originating calls or horizontal handover calls from near cells. C_w is the new state variable that represents the number of vertical handover calls from WLAN to cellular system. The third variable W, shows the calls in WLAN system.

IV. Scenario 1

A. Handover Model for Scenario 1

The first part of the analysis considers one originating call in the WLAN. A two-dimensional Markov chain is used and the analysis is performed using the method in [7]. Fig. 3 considers two random variables (*i*,*j*), where *i* denotes the number of calls in the cellular system when λ_c=0 and *j* represents number of originating calls in the WLAN. In this scenario, for simplicity and ease of explanation, we assume that the WLAN can have one call in the system and there are no originating calls in the cellular system as shown in Fig. 3.

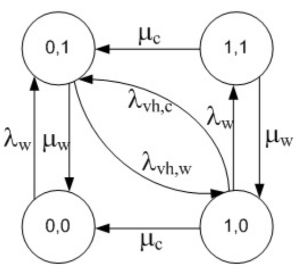

Fig. 3. The state diagram with an originating call in WLAN

There are two types of arrivals to the WLAN system. There are new originating calls with rate λ_w, or there may be a vertical handover from the cellular network with a rate of $\lambda_{vh,c}$. A new originating call first tries to get admission to the WLAN. The request is accepted if there is enough bandwidth to accommodate the call. The call in the WLAN may stay in the system until it gets a channel to be served. Since the users considered are mobile the call may leave the WLAN. In this case the call can be handed over to the 3G cellular network, requesting an admission. In addition, when a Markov chain with two random variables is considered, the call can be sent back to the WLAN coverage area at a rate of $\lambda_{vh,c}$ or can be served by cell with a service rate of μ_c. The WLAN system can generate an originating call in the system while the handover calls wait for service from the cellular system. However according to the scenario 1 there is a single call allowed into the system. When the system is busy, the following requests are blocked. Please note that it is not possible to differentiate the originating calls from the calls coming from WLAN within cellular system, when model in Fig. 3 is employed. This is clearly shown in Fig. 3 because the transitions from the WLAN to the cellular network is shown as (0,1) to (1,0) and the transitions from the cellular to the WLAN is shown as (1,0) to (0,1) hence the handover hysteresis is formed which represent the feedback loop that is observed in our results. Therefore, a new model is presented in this study to be able to separate the calls handed over from the WLAN.

B. The New Model for Scenario 1

The new model presented uses one additional random variable to represent the number of originating calls within the cellular network, and the number of calls handed over from WLAN separately. Considering the first scenario, state (i, k, j) shows that there are *i* number of requests in the cellular system originated in the cell, k number of requests in cellular system handed over from WLAN, and j number of originating calls in the WLAN. This model for scenario 1 is shown in Fig. 4. With careful modelling and mature admission control algorithms, both 3G cellular network and WLAN are assumed to support both vertical handovers with QoS provisioning. However due to handover hysteresis, request being handed over to 3G cellular system from WLAN should not be allowed back to the WLAN for QoS enhancement. The new model presented clearly differentiates calls in the cell from the calls that have already been handed over to the cell ($\lambda_{vh,w}$) by adding the new state (0,1,0). When the calls are handed over to the cellular system, they terminate in cellular network with service rate of μ_c or the integrated system can accommodate one originating call to the WLAN hence the (0,1,1) state is generated.

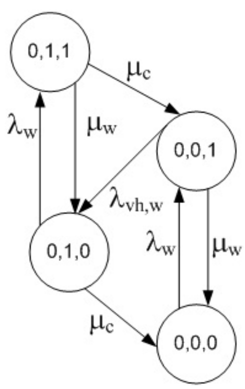

Fig. 4. The state diagram of new analytical model with a call in WLAN

The vertical handover from cell to WLAN and originating call in cellular system do not appear in the state diagram since only originating call in WLAN is considered for the first analysis. Hence the initial transition is from (0,0,0) to (0,0,1) which represents a call originating in the WLAN. Although $\lambda_c = 0$, please note that it is possible for the calls in the cellular system to do a downward vertical handover to the WLAN as long as they are in the coverage area of the WLAN (can be for better QoS especially in terms of bandwidth). The state probabilities $P_{i,j}$ can be obtained using the balance equations and solving the resultant system of simultaneous equations. From $P_{i,j}$, a number of steady-state performance measures can be computed. For illustration, we have concentrated on the mean queue length (MQL_{new_c}/ MQL_{new_w}) of both cellular system and WLAN respectively. MQL values can be obtained as:

$$MQL_{new_c} = P_{0,1,0} + P_{0,1,1}$$
$$MQL_{new_w} = P_{0,0,1} + P_{0,1,1}$$

C. Numerical Results

In this section, the performance results of scenario 1 for both handover model used in [7] and new proposed model are presented. For a fair comparison, the system parameters used are mainly taken from [7] based on the relevant literature and are given as $\mu_c = 0.0221$, $\mu_w = 0.0667$, $\lambda_w = 0.07$ calls per second, E_c[v]=40km/h, E_w[v]=2km/h, *R*=1000m, *r*=100m [4], [5], [7], [8], [9], [10], [11], [12], [13], [14] unless stated otherwise which correspond for specific dwelling times and velocities in the integrated system [7].

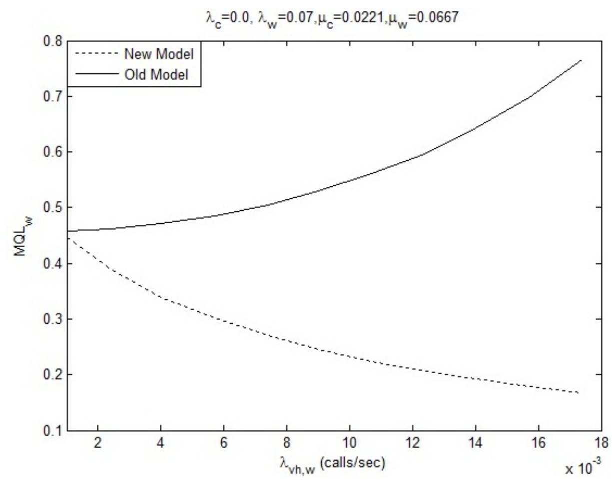

Fig. 5. Effect of the feedback streams on MQL_w for scenario 1

The MQL_w results are shown as a function of upward vertical handover from WLAN to the cellular system in Fig. 5 for scenario 1. A call tries to get admission to the cellular system. However, the request is rejected if there is not enough bandwidth to accommodate. Once the calls move to the cellular system, they shouldn't do a vertical handover back to the WLAN in order to avoid infinite loop. With the additional random variable, C_w it is possible to differentiate the handed over calls from the WLAN and avoid to re-transmission back to WLAN. Because the WLAN is within the coverage area of the cellular network, this provides an opportunity for users to remain connected to the 3G cellular network for better performance. Thus the results in Fig. 5 show that MQL_w for old model increases when the amount of upward vertical handover increases. This is mainly because the calls sent from WLAN to cellular system are allowed to do a downward vertical handover back to the WLAN. The MQL_w results obtained from the new model decreases as the amount of upward vertical handover increases because there will be less calls in the WLAN system. In other words, the results obtained from the new model shows the calls handed over from WLAN to the cellular system are not allowed back to the WLAN.

V. Scenario 2

A. Handover Model for Scenario 2

In this section a more complicated scenario is explored, where there are up to two calls in the cellular system and a single call in the WLAN has been considered in this section. The system is also analysed using two-dimensional Markov chain considered in [7] which contains only two state variables for state (i,j), where *i* and *j* are the numbers of calls in the cellular and WLAN, respectively. The two-dimensional Markov chain model with two originating calls in the cellular system and an originating call in WLAN is shown in Fig. 6.

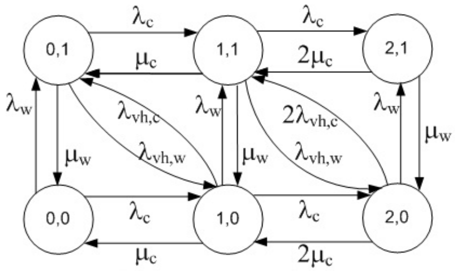

Fig. 6. The state diagram with two calls in cell and an originating call in WLAN

In the second scenario, the cellular system can accommodate up to two calls in the cell coverage area. The calls in the cellular system may stay in the cell until they get a channel to be served or leave the system to either WLAN or neighbouring cells due to mobility. In addition the calls handed over to the WLAN can do a vertical handover to the cellular system. On the other hand similar to the scenario 1, a call in WLAN may stay in the system until it gets a channel to be served, or can leave the system to the coverage area of cell.

It is shown in both Fig. 3 and Fig. 6 that the calls already handed over to the cellular system from WLAN are allowed to return back to WLAN. In other words the system is unable to differentiate between the originating calls in cellular network and the calls which have already been forwarded from WLAN. In the next section a new vertical handover model is presented for scenario 2 to differentiate vertical handover calls coming from WLAN to cellular system from the other calls. Thus, the integrated 3G cellular/WLAN system could behave as a practical life system. Even though the scenario 2 is not much more complicated than the scenario 1, the new handover model considered for scenario 2 becomes a much more complex Markov chain.

B. The New Model for Scenario 2

The new analytical model with two calls in cell and a call in WLAN system is shown in Fig. 7. A new model which is able to differentiate between originated calls in cellular systems and calls coming from WLAN as vertical handover is presented. A new state diagram is introduced to restrict the unexpected feedback streams from the WLAN to cellular and back to the WLAN.

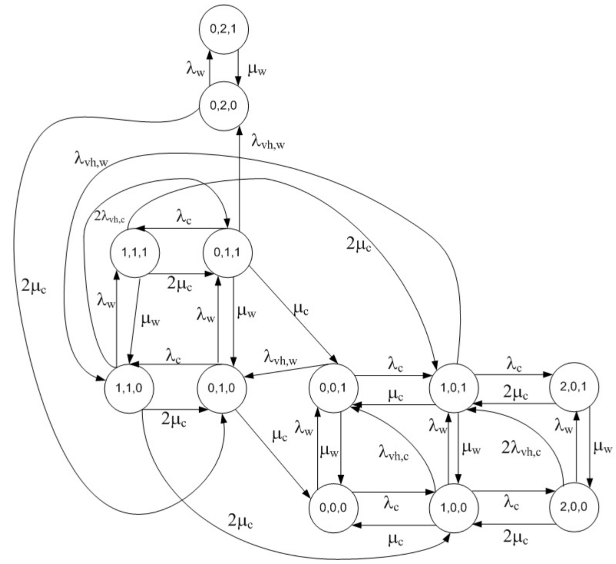

Fig. 7. The state diagram of new analytical model with two calls in cell and a call in WLAN

Applying the proposed model described in the previous sections, it is important to note that introducing a new random variable creates a new state for the system. In addition new state-variable should be automatically generated which is very difficult. This kind of behaviour makes the analytical solution of the model rather complex. The new analytical model is solved by using balance equations together with a system of simultaneous equations. The state probabilities are then used to calculate the mean queue length of the proposed model for both cellular and WLAN systems (MQL_{new_c}/ MQL_{new_w}) respectively as follows:

$$MQL_{new_c} = \sum_{i=0}^{2} iP_{i,0,0} + \sum_{i=0}^{2} iP_{i,0,1} + \sum_{i=0}^{1} P_{0,1,i} + \sum_{i=0}^{1} 2P_{1,1,i} + \sum_{i=0}^{1} 2P_{0,2,i}$$

$$MQL_{new_w} = \sum_{i=0}^{2} P_{0,i,1} + \sum_{i=0}^{1} P_{1,i,1} + P_{2,0,1}$$

In order to evaluate the performance of the scenario 2 using the proposed model, we propose a new Markov model by adding new state-variable to the system. The main modelling difficulty herein stems from the fact that the new state significantly increases the complexity of the system description and solution.

C. Numerical Results

As previously stated, the numerical results are given for a specific scenario (i.e. $I(t) \leq 2$ and $J(t) \leq 1$). The parameters used for numerical results are taken from the literature [4], [5], [7], [8], [9], [10], [11], [12], [13], [14]. Results are presented for $\mu_c = 0.0221$, $\mu_w = 0.0667$, $\lambda_c = 0.027$, $\lambda_w = 0.05$ calls per second, E_c[v]=40km/h, E_w[v]=2km/h, *R*=1000m, *r*=100m unless stated otherwise. The results presented clearly show the effects of feedback streams looping between WLAN and cellular systems. In Fig. 8 and Fig. 9, the effect of the unseen feedback streams of the second scenario on the cellular system and WLAN are presented for the both handover models (systems with two and three state variables respectively). Fig. 8 depicts the MQL_c results for scenario 2 as a function of vertical handover calls from WLAN to cellular system. It is clearly shown in Fig. 8 that, MQL_c results for new model increase more rapidly compared to the model with only two state variables. This is mainly because the vertical calls handed over are not re-transmitted back to WLAN. The calls stay in the cellular system and wait for service by the cellular network hence MQL_c increases.

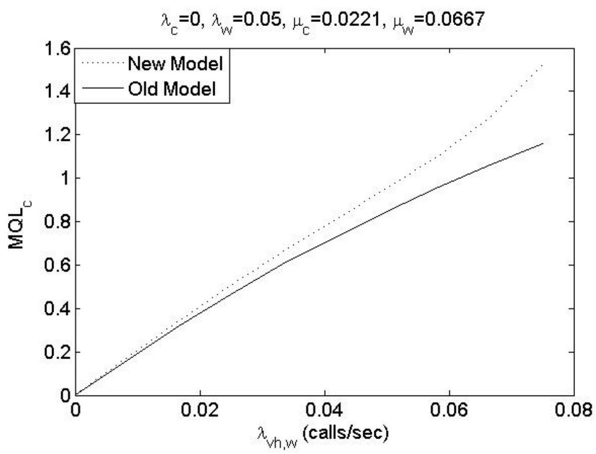

Fig. 8. Effect of the feedback streams on MQL_c for scenario 2

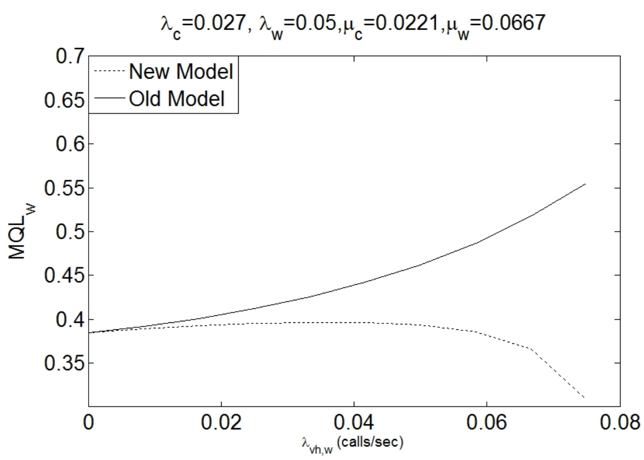

Fig. 9. Effect of the feedback streams on MQL_w for scenario 2

As the vertical handover rates from WLAN to cellular system increase the MQL_w is also affected considerably. More significantly Fig. 9 shows that increasing the amount of vertical handover calls increases the MQL_w in both scenarios when existing models are employed [7], [13], [14]. This is mainly due to the stream coming back from the cellular system to WLAN. However, in practice, once the requests are transferred to the cellular system from WLAN, they are not expected to be re-admitted to WLAN with a vertical handover from cellular system. This is accurately captured by the new model, which shows that as the upward vertical handover rate increases there will be less calls in the WLAN system because there is no longer any feedback from the cellular network. Therefore as the results obtained from the new model shows, the MQL_w is expected to decrease as the amount of vertical handover from WLAN to cellular system increase.

TABLE I
MQL RESULTS FOR BOTH SYSTEMS AND MODELS (D IS DIFFERENCE)

$\lambda_{vh,w}$	MQL_{new_w}	MQL_w	$D_{wlan}(\%)$	MQL_{new_c}	MQL_c	$D_{cell}(\%)$
0	0.457	0.4565	0	0	0	0
0.0083	0.452	0.458	1.26	0.174	0.161	7.142
0.0166	0.442	0.461	4.204	0.344	0.317	7.735
0.0249	0.429	0.466	8.635	0.506	0.465	8.178
0.0332	0.412	0.473	14.768	0.660	0.602	8.741
0.0415	0.392	0.483	23.080	0.884	0.729	17.422
0.0498	0.369	0.496	34.681	0.953	0.847	11.028
0.0581	0.338	0.514	52.34	1.105	0.958	13.289
0.0664	0.292	0.538	84.265	1.279	1.06	17.087

The results in Table I clearly show the effects of the feedback streams considering the second scenario when $\lambda_w = 0.07$. Originating calls in cellular system $\lambda_c = 0$ and effects of vertical handover is maximised since it is the only source of incoming requests to the cellular system. In other words MQL_{new_w} decreases as expected because there is no stream coming back from the cellular system to the WLAN. On the other hand MQL_c results for new model increase more rapidly compared to the old model. This is because calls coming back from the WLAN must be serviced by the slower cellular network since they cannot re-enter the faster the WLAN. Hence MQL_{new_c} increases in the new model compared to the old model. Even for smaller values of $\lambda_{vh,w}$ the difference in the results between the two models can be high. For instance $\lambda_{vh,w}$ = 0.0664 the difference between MQL_{new_w} and MQL_w is up to 84.265%.

The existing modelling approaches uses one state variable in order to represent the number of jobs in cellular system. Due to the restrictions of Markov property, they fail to classify the source of requests stored in the cellular system. The results indicate that the proposed model solves the unseen feedback streams problem.

VI. Conclusions and Future Work

In order to analyse the integration of vertical handover in future heterogeneous wireless networks, two stage queuing system models such as [1], [5], [7], [8], [9], [10], [13] and [14] have been proposed. Feedbacks during the vertical handover procedure in integrated cellular/WLAN system is a critical issue in analytical modelling which affects the quality of service (QoS) of the system [7].

We propose a new Markov model for cellular/WLAN system integration. The new model clearly differentiates requests originating in the cellular system, from requests being handed over from WLAN to cellular system, therefore the calls handed over from WLAN to cellular network are not allowed back to the WLAN. This prevents a handover hysteresis which our results show will severely affect system performance. The new model therefore is an improved model for studying handover in real systems. The proposed model is therefore important for the design of practical vertical handover schemes.

New model is definitely more accurate. However parameters and the generation of state-space should be automatically performed, and this process can become quite complicated. The model considered here gets complicated as the number of calls allowed in the systems increases. Hence more work is needed to automate the generation of the state diagrams and to solve the equations for the state probabilities in order to make this new model useful for more complex mobile systems.

As future research, exploring the use of guard channels as a way of benefiting from having reserved channels in 3G cellular networks should be taken into account. Such an approach would also allow us to differentiate the originating calls from vertical handover calls in system level (vertical calls would only be associated with reserved channels). The results will be compared with the results in this paper.

Furthermore, since the states of the system is quite complicated, it is desirable to use the existing methods for the automatic generation of the states similar to the approaches used in [16], [17].

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