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A Performance Study of Hierarchical Heterogeneous Wireless Integrated Networks

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Abstract: Next generation wireless network is envisioned to be heterogeneous, integrating a wide variety of wireless access networks with different coverage, capacity and mobility support. In general, the traffic volume can be very heavy in hot-spot areas and a higher data transfer rate can be provided by introducing another layer of wireless access. This can raise the utilization of the wireless channel and still achieve a good balance between user satisfaction and efficiency. In this paper, we analyse and evaluate a two-tier heterogeneous hierarchical overlay wireless network with different deployment. The integrated network is modelled as an open queueing network of loss systems. With the help of a logical network topology based analysis, the performance metrics of blocking and dropping probabilities are calculated using an Erlang fixed-pointed method. A number of hierarchical heterogeneous wireless integration system scenarios are set up and the numerical results are calculated and discussed.

Keywords: Hierarchical Cellular Structure, Heterogeneous Wireless Network, Macro-cell, Micro-cell

1 Introduction

Multiple radio access technologies are available for mobile terminals in a heterogeneous wireless network such as mobile users within WLAN hotspots that reside within 3G cells. It is commonly believed that the deployment of micro-cells in the traffic intensive areas will alleviate the traffic load of the macro-cell. Heterogeneous wireless networks tend to have a hierarchical overlaid structure in which macro-cells are adjacent to each other providing the overall service coverage, while micro-cells can be either adjacent or separate with limited coverage of hot-spot areas, like a shopping mall, airport or a busy office. Micro-cells are used to address the high-intensity traffic of mainly slow mobility areas, and macro-cells are overlaid over the micro-cells to cater mainly to high-mobility lower density traffic. The two tiers of microcells and macro-cells provide a secondary resource for new traffic as well as handovers for mobile subscribers of different mobility classes. [1] A macro-cell could be any Wide Area Network (WAN) technique like 3G, GSM/GPRS and WiMax; and micro-cell could be any high-speed, wide-band wireless Local Area Network (IEEE 802.11 family, HiperLAN etc.).

There has been a lot of research on heterogeneous wireless systems. Several effective pathways have been proposed in the study of specific heterogeneous wireless integrated system and most of them can be categorized into two groups based on the tools adopted. One group of study uses test-beds. For example, a test-bed is implemented in [2] to construct a real network architecture composed of several physical communication devices for the study of interworking of WiMax, 3G and WiFi. In [3] the authors build a test-bed for the evaluation of the handover method between WLAN and CDMA2000 1x Ev-Do system. The other group adopts various simulation approaches. In [4] a simulation based on

Network Simulator 2 (NS2) is built to evaluate the performance of the cellular/WLAN networks and in [5] simulation models constructed using MatLab are adopted to compare the performance difference between a WCDMA/WLAN interworking system and a TD-SCDMA/WLAN interworking system. The methods discussed above focus on realistic and straightforward situations. However, a highly detailed simulation model implies a large number of parameters and the meticulous implementation of every detail of a specific network increases the complexity of the model and hence such a model can usually be applied only to very limited situations. The test-bed methods also have this kind of problems (also the construction of a good test-bed will incur even more cost than simulation).

For a general heterogeneous wireless integrated system, especially the ones with a hierarchical structure, a mathematical model is preferable. The tool used in this kind of modelling is the queueing network. Open queueing network models with finite capacity have been successfully applied in many domains including computer science [6] and communication engineering [7]. It also has been used in [8] to model homogeneous hierarchical overlay wireless networks, but application in a general analytic model of a heterogeneous hierarchical overlay wireless is still very limited to just a few cellular/WLAN interworking systems. W. Song is the pioneer in this field and first introduced the method for hierarchical cellular networks into the study of a cellular/WLAN interworking system in [9]. Enrique follows up and in [10] he developed an analytic model using birth-death process. The difficulties in modelling mathematically complicated traffic features of a heterogeneous wireless integrated network (e.g. various handovers) were then solved when we introduced a novel network topology abstraction method in [11] to facilitate the analysis of complex handover traffic. We started to model a two-tier heterogeneous hierarchical overlay wireless network as open networks of loss systems for the first time in [12] to analyse the performance of such systems.

In this paper we further extend the work we have done in [12] with the help of the network topological conversion method to derive the abstract topological representation of a heterogeneous wireless integrated network. We then apply the queueing network modelling approach to evaluate the performance of a heterogeneous wireless integrated system, in terms of QoS metrics such as new call blocking probability and handover call dropping probability.

The remainder of this paper is organized as follows. In section 2 the system model is discussed including the logical network topology conversion and node and link traffic analysis, while the results are given and commented in section 3. Section 4 concludes the paper.

2 System Model

2.1. Logical Network Topology Conversion

In this paper we only consider a two-tier hierarchical wireless network system in which one or more overlaying micro-cells are deployed inside each macro-cell. But theoretically more than 2 tiers hierarchical system can also be analysed using this method. All the mobile terminals are dual-mode, i.e. they have a radio interface to the wireless access networks of both the macro-cells and the micro-cells.

We use the logical topology abstraction method that was proposed in [11] to derive the network topology of the system by mapping each macro-cell and micro-cell as nodes and handover traffic as links. Handover can only happen when there is a link between two nodes, indicating that they are either adjacent or overlaid to each other as shown in Figure 2.1. Two types of links exist in the graph. One type shown as a continuous line represents horizontal handover between homogeneous networks and the other shown as a dashed line represents vertical handover between heterogeneous networks. More detailed and complete description on network topology conversion can be found in [13]. Two-tier overlay structure and the handover relation among different networks are well illustrated in this manner.

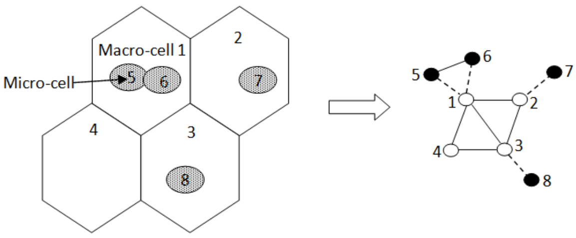


Figure 2.1: A two-tier hierarchical heterogeneous overlay wireless integrated network deployment and its converted network topological representation.

Generally speaking, most of the mobile terminals in hot-spots are low speed and consequently we can set up one or more microcells within each macro-cell to address the traffic load imbalance problem.

We define M_i^a as the set of macro-cell nodes connected to macro-cell i, i.e., all the macro-cells adjacent to macro-cell i; m_i^o as the set of micro-cell nodes connected to macro-cell node i, i.e., all the micro-cells inside the coverage of macro-cell i (overlaid micro-cells); m_k^a as the set of micro-cell nodes connected to micro-cell node k, i.e., all the micro-cells adjacent to micro-cell k, and M_k^o as the set of macro-cell nodes connected to micro-cell node k, i.e., all the overlaying cells of micro-cell k.

The capacity of each macro-cell is C_i^M, and the capacity of each micro-cell k is C_k^m. Let R_i^M (R_k^m) denote the number of guard channels reserved in macro-cell i (micro-cell k) for the handover call. R_i^M, R_k^m provide the admission control to the system. When the number of connections in macro-cell i is less than $C_i^M - R_i^M$, it accepts both new calls and handover calls, but when the number of connections in macro-cell i (micro-cell k) surpasses $C_i^M - R_i^M$ ($C_k^m - R_k^m$), only handover requests can be accepted for the cut-off admission policy. For the fractional guard channel policy, new call request is accepted with the probability ω_i^M (ω_k^m). Some of the important parameters are defined in Table 2.1.

Table 2.1: Summary of important parameters in the study of a hierarchical heterogeneous wireless integrated network.

Symbol	Definition
k_i^M / k_k^m	**The number of the cell or WLAN in the cellular/WLAN system**
C_i^M / C_k^m	**Macro-cell/Micro-cell capacity**
R_i^M / R_k^m	**Guard channels of macro-cell *i* /micro-cell *k* for handover connection**
M_i^a	**Set of macro-cell nodes connected to macro-cell *i***
m_i^o	**Set of micro-cells inside the coverage of macro-cell *i***
m_k^a	**Set of micro-cells adjacent to micro-cell *k***
M_k^o	**Set containing the overlaying macro-cell of micro-cell *k***

2.2. Node (Cell) Traffic Analysis

First of all, we can observe the traffic flow pattern on each node which is a representation of either a macro-cell or a micro-cell on the base station level in the system and this is shown in Figure 2.2 below. Based on the principle of traffic flow conservation (that all the traffic flows into a node and out of the same node should be equal), the relations among different flows coming into and out of each node thus can be established.

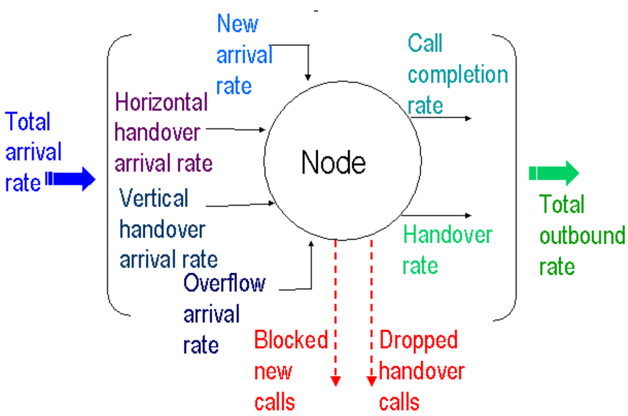


Figure 2.2: Traffic flow pattern in each node (macro-cell or micro-cell) [12] for a two-tier hierarchical heterogeneous overlay wireless integrated network.

The overall incoming traffic to each node can be divided into new traffic, horizontal handover traffic (traffic from adjacent homogeneous cells), vertical handover traffic (traffic from overlaid heterogeneous cells) and overflow traffic (handover traffic from this cell rejected by the receiving cells and flow back in) as shown in Fig. 2.2. As an open network, the new traffic $\lambda_i^{(Mn)}$ ($\lambda_k^{(mn)}$) comes from outside, while handover traffic and overflow traffic moving among the nodes along the links are always flowing within the system. This is represented in equation (2.1).

$$\lambda_i^M(k_i^M) = \begin{cases} \lambda_i^{(Mn)} + \sum_{j\in C_i^a} \lambda_{ji}^{(MM)} + \sum_{k\in W_i^o} \lambda_{ki}^{(mM)} + \sum_{l\in W_i^o} \lambda_{li}^{(mo)}, & k_i^M \le C_i^M - R_i^M \\ \lambda_i^{(Mn)}\omega_i^M + \sum_{j\in C_i^a} \lambda_{ji}^{(MM)} + \sum_{k\in W_i^o} \lambda_{ki}^{(mM)} + \sum_{l\in W_i^o} \lambda_{li}^{(mo)}, & k_i^M > C_i^M - R_i^M \end{cases} \quad (2.1)$$

$$\lambda_k^m\left(k_i^m\right) = \begin{cases} \lambda_k^{(mn)} + \sum_{l\in W_k^a} \lambda_{lk}^{(mm)} + \sum_{j\in C_k^o} \lambda_{jk}^{(Mm)} + \sum_{g\in C_k^o} \lambda_{gk}^{(Mo)}, & m_k \le C_k^m - R_k^m \\ \lambda_k^{(mn)}\omega_k^m + \sum_{l\in W_k^a} \lambda_{lk}^{(mm)} + \sum_{j\in C_k^o} \lambda_{jk}^{(Mm)} + \sum_{g\in C_k^o} \lambda_{gk}^{(Mo)}, & m_k > C_k^m - R_{k\ i}^m \end{cases} \quad (2.2)$$

The outgoing traffic consists of two parts. One in the form of the total rate of channel completions at each node due to either a channel becoming free because the call has been completed normally or because it is handed over to another node is therefore $\mu_i^{(M)} + \nu_i^{(M)}$ in macro-cell i ($\mu_k^{(m)} + \nu_k^{(m)}$ in micro-cell k), i.e., $1/(\mu_i^{(M)} + \nu_i^{(M)})$ is the mean channel holding time at macro-cell i, $1/(\mu_k^{(m)} + \nu_k^{(m)})$ in micro-cell k. ω_i^M and ω_k^m are factors used to control the percentage of new calls that can use the reserved channels for handover calls in each macro-cell and micro-cell.

Then the system can be modelled as an open network of queues with each node as a loss system. The number of connections in each node evolves according to an irreducible birth-death process with birth rate λ_i^M in a macro-cell node, λ_k^m in a micro-cell node, and death rate $\left(\mu_i^{(M)}+\nu_i^{(M)}\right)\cdot n_i^M$ in a macro-cell node, $\left(\mu_k^{(m)}+\nu_k^{(m)}\right)\cdot n_k^m$ in a micro-cell node.

2.3. Link (Handover) Traffic Analysis

We now focus on the traffic flow on the links, i.e., handover traffic and overflow traffic to derive the handover rates in equation (2.1) and equation (2.2). First let us assume that a call in macro-cell i may either finish and leave the system at the end of its holding time with a probability of $T_i^{(M)}$, or move within the system and continue in an adjacent macro-cell or micro-cell node with probability $1-T_i^{(M)}$ which is the sum of probabilities that the call goes to any adjacent nodes.

So we have $1-T_i^{(M)}=\sum_{j\in W_i^a}H_{ij}^{(MM)}+\sum_{k\in m_i^o}H_{ik}^{(Mm)}$, where $H_{ij}^{(MM)}$ is the probability to attempt a horizontal handover to adjacent cell j, and $H_{ik}^{(Mm)}$ is the probability to attempt a vertical handover to micro-cell k inside macro-cell i.

Similarly, in micro-cell we can obtain $1-T_k^{(m)}=\sum_{l\in m_k^a}H_{kl}^{(mm)}+\sum_{i\in M_k^o}H_{ki}^{(mM)}$, where $H_{kl}^{(mm)}$ is the probability of attempting a horizontal handover to adjacent micro-cell l, $H_{ki}^{(mM)}$ is the probability of attempting a vertical handover to overlaying macro-cell i.

For m macro-cells and $n-m$ micro-cells in an integrated system, the handover probabilities can be given in the form of a matrix as given in equation (2.3).

$$H=\begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1m} & \cdots & H_{1n} \\ H_{21} & H_{22} & \cdots & H_{2m} & \cdots & H_{2n} \\ \vdots & \vdots & \ddots & \vdots & \cdots & \vdots \\ H_{m1} & H_{m2} & \cdots & H_{mm} & \cdots & H_{mn} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ H_{n1} & H_{n2} & \cdots & H_{nm} & \cdots & H_{nn} \end{bmatrix} \quad (2.3)$$

We define this matrix as the handover probability matrix and it is composed of 4 parts representing the entire handover situation in the system including horizontal handover probabilities between macro-cells and micro-cells as shown in Figure 2.3.

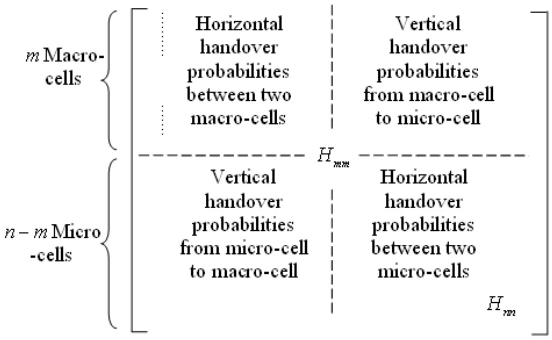


Figure 2.3: Composition and structure of the handover probability matrix [12] of an integrated heterogeneous wireless system with m Macro-cells and n-m Micro-cells.

The blocking and dropping probabilities and the overall call arrival rate at each node are interdependent. Listing all the handover traffic formulae together with the node traffic formulae to form a set of non-linear equations allows these to be solved numerically by successive substitution to obtain the blocking and dropping probabilities in the system. The detailed discussion on the algorithm to calculate the blocking and dropping probabilities can be found in [12].

3 Results and Discussion

A hierarchical heterogeneous wireless integrated network with 4 identical macro-cells and 4 identical micro-cells is used, with different ways of deployment, in our analytical modelling in order to compare the results. Table 3.1 summarizes the simulation parameters used in the numerical experiments of all the scenarios.

Table 3.1: Parameters setting for the scenarios of a hierarchical heterogeneous wireless integration system with 4 identical macro-cells and 4 identical micro-cells.

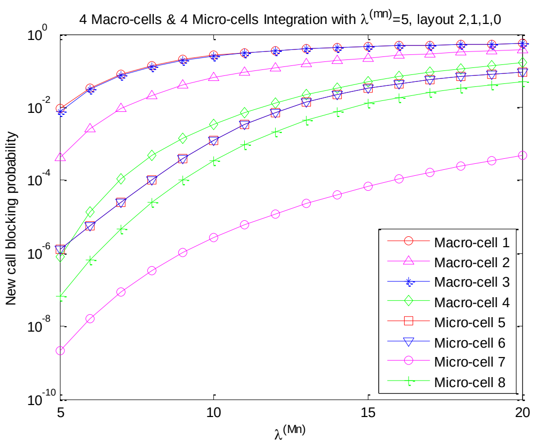
Parameter	Value
Number of macro-cell nodes N^M	3
Number of micro-cell nodes N^w	3
Capacity of each cellular node C_i^M	30
Capacity of each WLAN node C_k^m	60
Guard channels for handover traffic in macro-cell	2
Guard channels for handover traffic in micro-cell	2
Channel holding time for macro-cell node $1/\mu_i^M$	1 min
Channel holding time for micro-cell node $1/\mu_k^m$	4 min
Coverage factor R_{jk}	0.65

The new call arrival rate in micro-cell $\lambda^{(mn)}$ is fixed at 5 connections per minute while the new call arrival rate in macro-cell $\lambda^{(Mn)}$ is increased from 5 to 20 connections per minute.

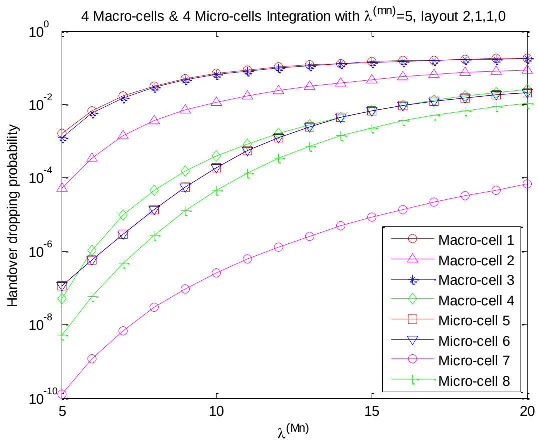
A micro-cell normally has a higher bandwidth than a macro-cell. This is reflected here as the network capacity as it can be seen that the capacity of a micro-cell node is double the size of a macro-cell node. Channel holding time reflects the user mobility level. So here micro-cell nodes are given a longer channel holding time because the user mobility is much lower in micro-cell than in macro-cell, i.e. the mobile terminals tend to stay longer in a micro-cell node than in a macro-cell node. Coverage difference is reflected in the coverage factor which is the ratio of the coverage area of a micro-cell to a macro-cell.

The first scenario whose deployment and network topology representation is shown in Figure 2.1 is set up and evaluated following the procedures described in the previous section. The calculated new call blocking probabilities and handover dropping probabilities are shown in Figure 3.1.

We can observe from Fig.3.1 that macro-cell 1 (as expected) has the highest new call blocking probabilities and handover dropping probabilities. This is due to the heavier traffic in macro-cell 1 as it has five handover traffic links both vertically and horizontally connected. Micro-cell 7 has the lowest call blocking and handover dropping probabilities since it only has one handover link which is connected to node 2, and node 2 in turn just has two horizontal handover links connected. While the micro-cell also only has one vertical handover link, it is connected to node 3, which in turn has 3 horizontal links. So a heavier traffic is expected.



(a)



(b)

Figure 3.1: Call blocking probabilities (a) and handover dropping probabilities (b) for a 4 macro-cells and 4 micro-cells integration system with layout pattern as 2, 1, 1, 0.

It also can be observed from the logical network topology that a local symmetric structure is presented in micro-cells 5 and 6, within macro-cell 1. Therefore we can expect identical performance in micro-cell 5, 6 and this is also reflected in Fig.3.1 as the curves of blocking and dropping probabilities for these two cells are exactly matched with each other.

The more links one node has, the heavier the traffic. Therefore performance will be affected in the form of higher blocking and dropping probabilities.

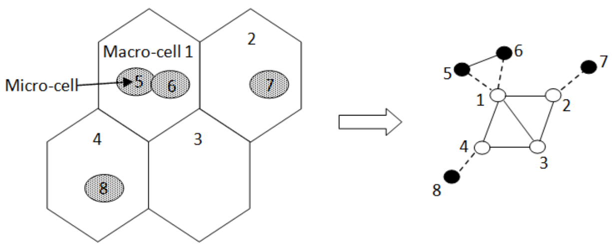
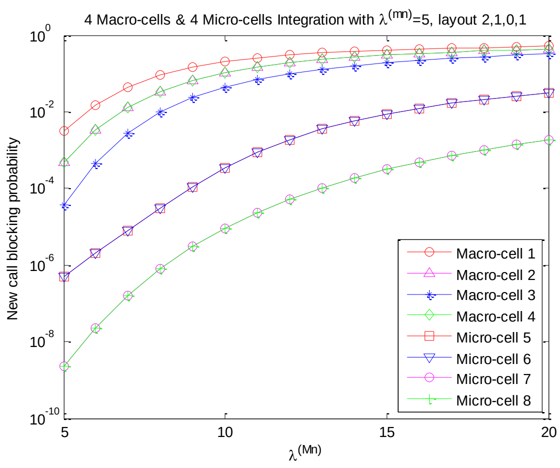


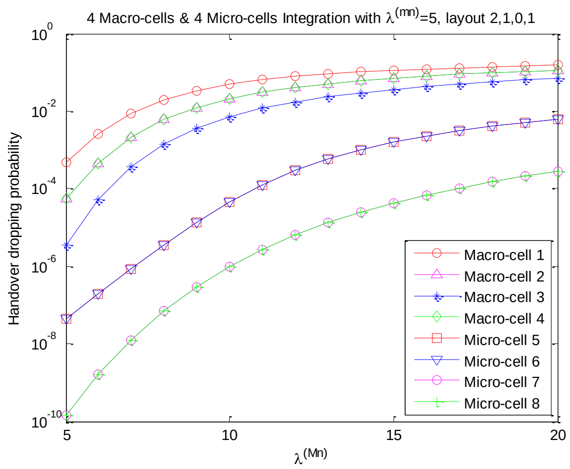
Figure 3.2: A two-tier hierarchical heterogeneous overlay wireless integrated network deployment and its converted network topological representation.

The second scenario is given in Fig.3.2 with the same number of macro-cells and micro-cells but different deployment thus different logical network topology.

Though the deployment of this scenario is very similar to the last one with still two adjacent micro-cells in macro-cell 1, and one single micro-cell in two of macro-cells, we observe from the network topology graph that more symmetry can be found in this scenario in the cases of micro-cell 5 and micro-cell 6, macro-cell 2 and macro-cell 4 and micro-cell 7 and micro-cell 8.



(a)



(b)

Figure 3.3: Call blocking probabilities (a) and handover dropping probabilities (b) for a 4 macro-cells and 4 micro-cells integration system with layout pattern as 2, 0, 1, 1

All these symmetries are reflected in the results displayed in Fig.3.3. The performance curves of macro-cell 2 are identical to the curves of macro-cell 4, as are the curves of micro-cell 7 and micro-cell 8 and curves of micro-cell 5 and micro-cell 8. Macro-cell 1 and macro-cell 3 is the only pair that doesn't have traffic symmetry, and macro-cell 3 apparently has less handover links to it. So the performance of macro-cell 3 is better than macro-cell 1, reflected in the lower new call blocking and handover dropping probabilities.

It can be observed that we can easily predict the traffic distribution and make some reasonable predictions from the network topological representation of the integrated system along. The convenience will become more obvious when a much more complicated integrated system is under investigation.

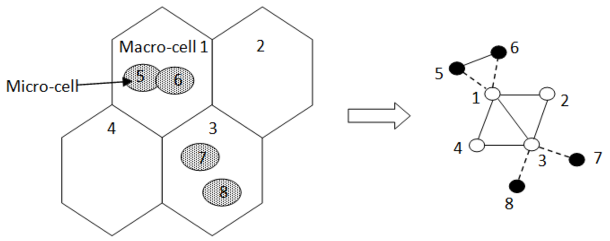
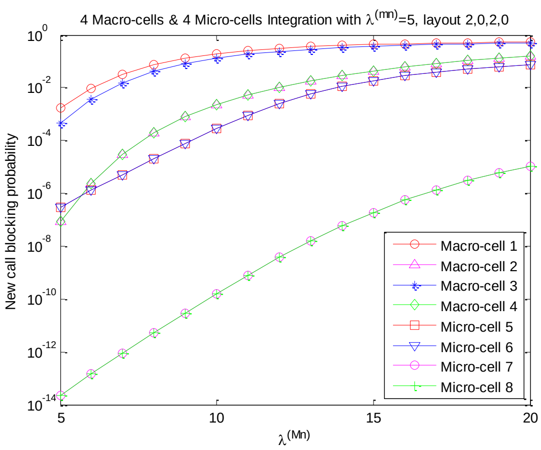
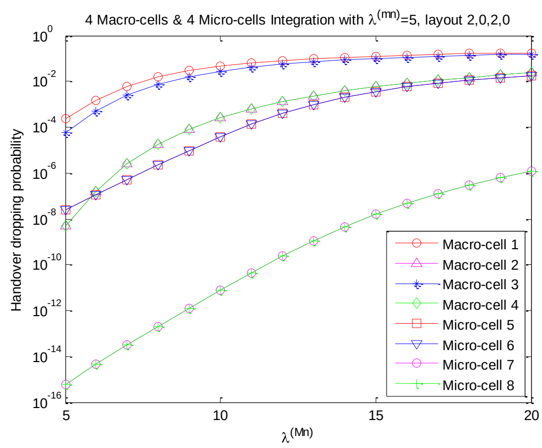


Figure 3.2: A two-tier hierarchical heterogeneous overlay wireless integrated network deployment and its converted network topological representation

In the last scenario, both macro-cell 1 and macro-cell 3 have two micro-cells overlaid within them. The two micro-cells 5 and 6 located within macro-cell 1 are, as in previous scenarios, adjacent to each other, and micro-cell 7 and 8 located within macro-cell 3 are separate.



(a)



(b)

Fig. 3.4. Call blocking probabilities (a) and handover dropping probabilities (b) for a 4 macro-cells and 4 micro-cells integration system with layout pattern as 2, 0, 2, 0

Also three pairs of cells are in symmetry in this scenario, as reflected in the results in Fig.3.4. But the location of micro-cell 7 and 8 both in macro-cell 3 this time makes the logical network topology of the whole system just one step away from full symmetry. If micro-cell 7 and 8 are connected by a continuous line (or in another word they are adjacent to each other thus making horizontal handover possible between them), then macro-cell 1 and 3 will also be paired together in symmetry. So the performances of macro-cell 1 and 3 are very close this time as the traffic flows are very similar within both nodes.

6 Conclusions and Future Work

In this paper, we discuss some of the most widely used approaches in the analysis of heterogeneous wireless integrated networks and the latest development of analytical modelling in the study of hierarchical heterogeneous wireless integration systems. We use logical network topology conversion, which is a powerful tool in the modelling of this kind of systems, and especially good in sorting out the handover relationships. Three scenarios are set up and their performances are evaluated using the method discussed. The results show the capability of the network topology method in the performance evaluation of such systems.

However, there are still many problems that need to be considered in future research, such as potentially heavy tailed behavior of the mobile's residence time. Another issue is how to seek a more appropriate method of addressing the handover traffic triggered by the load-balancing requirement, apart from the user mobility triggered one that we use in our model.

Acknowledgements

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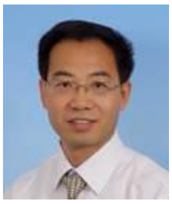

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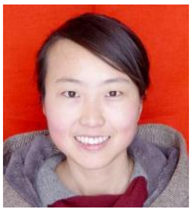

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