Globally Optimal User-Network Association in an 802.11 WLAN & 3G UMTS Hybrid Cell

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Abstract. With more and more users subscribing to wireless broadband services, it is desirable for them to have access to both WLAN and UMTS networks. We study globally optimal user-network association in an integrated WLAN and UMTS *hybrid cell*. The association problem is formulated as a generic MDP (Markov Decision Process) connection routing decision problem. In the formulation, mobile arrivals are assumed to follow Poisson process and a *uniformization* technique is applied in order to transform the otherwise state-dependent mobile departures into an i.i.d. process. We solve the MDP problem using a particular network model for WLAN and UMTS networks and with rewards comprising financial gain and throughput components. The corresponding Dynamic Programming equation is solved using Value Iteration and a stationary optimal policy with neither convex nor concave type switching curve structure is obtained. Threshold type and symmetric switching curves are observed for the analogous homogenous network cases.

1 Introduction

As 802.11 WLANs and 3G UMTS cellular coverage networks are being widely deployed, network operators are seeking to offer seamless and ubiquitous connectivity for high-speed wireless broadband services, through integrated WLAN and UMTS hybrid networks. For efficient performance of such an hybrid network, one of the core decision problems that a network operator is faced with is that of optimal user-network association or load balancing, i.e., optimally routing an arriving mobile user's connection to one of the two constituent networks. We study this decision problem assuming a specific network model for the WLAN and UMTS networks. To be more precise, consider a hybrid network comprising two independent 802.11 WLAN and 3G UMTS networks, that offers connectivity to mobile users arriving in the combined coverage area of these two networks. By independent we mean that transmission activity in one network does not create interference in the other. Our goal in this paper is to study the dynamics of optimal user-network association in such a WLAN-UMTS hybrid network. We concentrate only on streaming and interactive (HTTP like) data transfers.

Note that we do not propose a full fledged cell-load or interference based connection admission control (CAC) policy in this paper. We instead assume that a CAC precedes the association decision control. A connection admission decision is taken by the CAC controller before any mobile is considered as a candidate to be connected to either of the WLAN or UMTS networks. Thereafter, an association decision only ensures an optimal performance of the hybrid cell and it is not proposed as an alternative to the CAC decision.

In the network model for WLAN and UMTS networks, we introduce certain simplifying assumptions to make the MDP formulation analytically tractable. Without these assumptions it may be very hard to study the dynamics of user-network association in a WLAN-UMTS hybrid network.

1.1 Related Work and Contributions

Study of WLAN-UMTS hybrid networks is an emerging area of research and not much related work is available. Authors in some related papers [1–7] have studied issues such as vertical handover and coupling schemes, integrated architecture layout, radio resource management (RRM) and mobility management. However, questions related to load balancing or optimal user-network association have not been explored much. Premkumar et al. in [8] propose a *near optimal* solution for a hybrid network within a combinatorial optimization framework, which is different from our approach. To the best of our knowledge, ours is the first attempt to present a generic formulation of the user-network association problem under an MDP decision control framework. Moreover, this work is the first we know of that obtains an explicit optimal association policy for the specific WLAN-UMTS hybrid network model that we consider.

2 Framework for the Decision Control Problem

A hybrid network may be composed of several 802.11 WLAN Access Points (APs) and 3G UMTS Base Stations (NodeBs) that are operated by a single network operator. However, our focus is only on a single pair of an AP and a NodeB that are located sufficiently close to each other so that mobile users arriving in the combined coverage area of this AP-NodeB pair have a choice to connect to either of the two networks. We call the combined coverage area of a single AP cell and a single NodeB micro-cell [12] as a *hybrid cell*. The cell coverage radius of a UMTS micro-cell is usually around $400m$ to $1000m$ whereas that of a WLAN cell varies from a few tens to a few hundreds of meters. Therefore, some mobiles arriving in the hybrid cell may only be able to connect to the NodeB, either because they fall outside the transmission range of the AP or they are equipped with only 3G technology electronics. While other mobiles that are equipped with only 802.11 technology can connect exclusively to the WLAN AP. Apart from these two categories, mobiles equipped with both 802.11 WLAN and 3G UMTS technologies can connect to any one of the two networks.

The decision to connect to either of the two networks may involve a utility criteria that could comprise the total packet throughput of the hybrid network. Moreover, the connection or association decision involves two different possible decision makers, the mobile user and the network operator. We focus only on the globally optimal control problem in which the network operator dictates the decision of mobile users to connect to one of the two networks, so as to optimize a certain global cell utility. In Section 3, we model this global optimality problem under an MDP (Markov Decision Process) control framework. Our MDP control formulation is a *generic* formulation of the user-network association problem in a WLAN-UMTS hybrid network and is independent of the network model assumed for WLAN and UMTS networks. Thereafter in Section 5, we solve the MDP problem assuming a particular network model (described in Section 4) which is based on some reasonable simplifying assumptions.

2.1 Mobile Arrivals

We model the hybrid cell of an 802.11 WLAN AP and a 3G UMTS NodeB as a two-server processing system (Figure 1) with each server having a separate finite capacity of M_{AP} and M_{3G} mobiles, respectively. Further clarifications regarding the capacity of each server will be given later in Sections 4.2 and 4.3. For simplification we assume that mobile users are stationary, having no mobility. As discussed previously, mobiles are considered as candidates to connect to the hybrid cell only after being admitted by a CAC such as the one described in [9]. Some of the mobiles (after they have been admitted by the CAC) can connect only to the WLAN AP and some others only to the UMTS NodeB. These two set of mobiles (or sessions) are each assumed to constitute two separate dedicated arrival streams with Poisson rates λ_{AP} and λ_{3G}, respectively. The remaining set of mobiles which can connect to both networks form a common arrival stream with Poisson rate λ_{AP3G}. The mobiles of the two dedicated streams can either directly join their respective AP or NodeB network without any connection decision choice involved, or they can be rejected. For mobiles of common stream, either a rejection or a connection routing decision has to be taken as to which of the two networks will the arriving mobiles join while optimizing a certain utility.

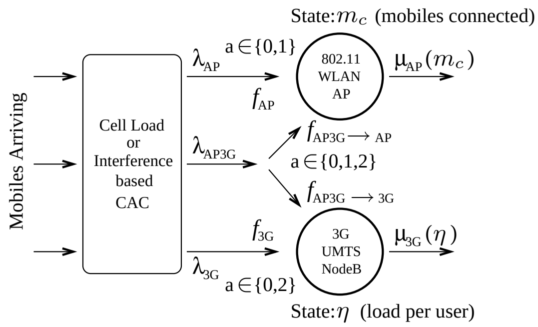

Fig. 1. Hybrid cell scenario

2.2 Service Requirements and Departure Rates

It is assumed that all arriving mobiles have a downlink data service requirement which is exponentially distributed with parameter ζ. In other words, every arriving mobile seeks to download a data file of average size $1/\zeta$ bits on the downlink. Let $\theta_{AP}(m_c)$ denote the downlink packet (or file) throughput of each mobile in the AP network when m_c mobiles are connected to it at any given instant. If η_{DL} denotes the *total cell load* in downlink of the NodeB cell, then assuming N active mobiles to be connected to the NodeB, $\eta \stackrel{\Delta}{=} \frac{\eta_{DL}}{N}$ denotes the average *load per user* in the cell (Chapter 8 in [12]). Let $\theta_{3G}(\eta)$ denote the downlink packet (or file) throughput of each mobile in the NodeB network when its average load per user is η. With the above notations, the effective departure rates of mobiles (or sessions) from each network or server can be denoted by,

$$\mu_{AP}(m_c) = \zeta \times \theta_{AP}(m_c) \tag{1}$$

and

$$\mu_{3G}(\eta) = \zeta \times \theta_{3G}(\eta). \tag{2}$$

3 MDP Control Formulation

As mentioned previously, for a globally optimal decision control it is the network operator that takes the decision for each mobile as to which of the AP or NodeB networks the mobile will connect to, after it has been admitted into the hybrid cell by the CAC controller (Figure 1). Since decisions have to be made in continuous time, this gives a *continuous time* MDP structure [18] to the decision problem and we state the equivalent MDP problem as follows:

- *States:* The state of a hybrid cell system is denoted by the tuple (m_c, η) where m_c ($m_c \in \mathbb{Z}, 0 \leq m_c \leq M_{AP}$) denotes the number of mobiles connected to the AP and η ($\eta \in \mathbb{R}, 0.05 \leq \eta \leq 0.9$) is the load per user of the NodeB cell (see Sections 4.2 & 4.3 for details on bounds for m_c and η).
- *Events:* We consider two distinguishable events: (i) arrival of a new mobile after it has been admitted by CAC and (ii) departure of a mobile after service completion.
- *Decisions:* For mobiles arriving in the common stream a decision action $a \in \{0, 1, 2\}$ has to be taken. $a = 0$ represents rejecting the mobile, $a = 1$ represents routing the mobile connection to AP network and $a = 2$ represents routing the mobile connection to NodeB network. For the dedicated arrival streams to AP and NodeB, a decision action $a \in \{0, 1\}$ and $a \in \{0, 2\}$, respectively, has to be taken.
- *Rewards:* Whenever a new incoming mobile is either rejected or routed to one of the two networks, it generates an instantaneous *state dependent* reward. $R_{AP}(m_c, \eta; a)$ and $R_{3G}(m_c, \eta; a)$ denote the rewards generated at dedicated arrival streams for AP and NodeB, respectively, when action 'a' is taken and the state of the system is (m_c, η). Similarly, $R_{AP3G}(m_c, \eta; a)$ denotes the reward generated at the common stream.
- *Criterion:* The optimality criterion is to maximize the total expected discounted reward over an infinite horizon and obtain a *deterministic* and *stationary* optimal policy.

Note that in the MDP problem statement above, state transition probabilities have not been mentioned because depending on the action taken, the system moves into a unique new state deterministically, i.e., w.p. 1. For instance when action $a = 1$ is taken, the state evolves from (m_c, η) to the unique new state $(m_c + 1, \eta)$.

Now, it is important to see that though events corresponding to mobile arrivals follow the Poisson process and are i.i.d., events corresponding to mobile departures are not i.i.d.. This is so because the departure rate of mobiles in both AP and NodeB depends on the state of the system (Equations 1 & 2) and is not fixed. However, applying the well-known *uniformization* technique from [17] we can introduce *virtual* (or dummy) departure events in the departure process. We can thus say that events (i.e., both arrival and departure) occur at the jump times of the combined Poisson process of all types of events with rate $\Lambda := \lambda_{AP} + \lambda_{3G} + \lambda_{AP3G} + \check{\mu}_{AP} + \check{\mu}_{3G}$, where $\check{\mu}_{AP} := \max_{m_c} \mu_{AP}(m_c)$ and $\check{\mu}_{3G} := \max_{\eta} \mu_{3G}(\eta)$. The departure of a mobile is now considered as either a real departure or a virtual departure. Then, any event occurring corresponds to an arrival on the dedicated streams with probability λ_{AP}/Λ and λ_{3G}/Λ, an arrival on the common stream with probability λ_{AP3G}/Λ, a real departure with probability $\mu_{AP}(m_c)/\Lambda$ or $\mu_{3G}(\eta)/\Lambda$ and a virtual departure with probability $1 - (\lambda_{AP} + \lambda_{3G} + \lambda_{AP3G} + \mu_{AP}(m_c) + \mu_{3G}(\eta))/\Lambda$. As a result, the time *periods* between consecutive events (including virtual departures) are i.i.d. and we can consider an $n-$stage *discrete time* MDP decision problem [18]. Let $V_n(m_c, \eta)$ denote the maximum expected $n-$stage discounted reward for the hybrid cell when the system is in state (m_c, η). The stationary optimal policy that achieves the maximum total expected discounted reward over an infinite horizon can then be obtained as a solution of the $n-$stage problem as $n \to \infty$ [18].

The discount factor is denoted by γ ($\gamma \in \mathbb{R}, 0 < \gamma < 1$) and determines the relative worth of present reward v/s future rewards. State (m_c, η) of the system is observed right after the occurrence of an event, for example, right after a newly arrived mobile in the common stream has been routed to one of the two networks, or right after the departure of a mobile. Given that an arrival event has occurred and that action 'a' will be taken for this newly arrived mobile, let $U_n(m_c, \eta; a)$ denote the maximum expected $n-$stage discounted reward for the hybrid cell when the system is in state (m_c, η). We can then write down the following recursive Dynamic Programming (DP) [18] equation to solve our MDP decision problem,

$\forall n \geq 0$ and $0 \leq m_c \leq M_{AP}$, $0.05 \leq \eta \leq 0.9$,

$$
\begin{aligned}
V_{n+1}(m_c, \eta) = & \frac{\lambda_{AP}}{\Lambda} \max_{a \in \{0,1\}} \{R_{AP}(m_c, \eta; a) + \gamma\, U_n(m_c, \eta; a)\} \\
& + \frac{\lambda_{3G}}{\Lambda} \max_{a \in \{0,2\}} \{R_{3G}(m_c, \eta; a) + \gamma\, U_n(m_c, \eta; a)\} \\
& + \frac{\lambda_{AP3G}}{\Lambda} \max_{a \in \{0,1,2\}} \{R_{AP3G}(m_c, \eta; a) + \gamma\, U_n(m_c, \eta; a)\} \\
& + \frac{\mu_{AP}(m_c)}{\Lambda} \gamma\, V_n(m_c', \eta) \\
& + \frac{\mu_{3G}(\eta)}{\Lambda} \gamma\, V_n(m_c, \eta') \\
& + \frac{\Lambda - (\lambda_{AP} + \lambda_{3G} + \lambda_{AP3G} + \mu_{AP}(m_c) + \mu_{3G}(\eta))}{\Lambda} \gamma\, V_n(m_c, \eta),
\end{aligned}
\tag{3}
$$

where, states (m_c', η) and (m_c, η') are the new states that the system evolves into when a departure occurs at AP and NodeB, respectively. The fact that dedicated stream mobiles can only join one network or the other has been incorporated in the first two terms in R.H.S. Equation 3 is a very generic formulation of our user-network association decision problem and it can be solved using any particular definition for the rewards and the new states (m_c', η) and (m_c, η'). In Section 5, we will solve the DP formulation of Equation 3 assuming a specific definition for the rewards based on throughput expressions obtained from a specific network model for the WLAN and UMTS networks. We first present this network model in the following section along with some simplifying assumptions.

4 WLAN and UMTS Network Models

Before discussing the network models adopted from previous work, we first state below some simplifying assumptions along with their justification. Since the bulk of data transfer for a mobile engaged in streaming or interactive data transmission is carried over the downlink (AP to mobile or NodeB to mobile) and since TCP is the most commonly used transport protocol (streaming protocols based on TCP also exist, e.g., Real Time Streaming Protocol), we are interested here in network models for computing TCP throughput on only downlink.

4.1 Simplifying Assumptions

Assumption on QoS and TCP: We assume a single QoS class of arriving mobiles so that each mobile has an identical minimum downlink throughput requirement of θ_{min}, i.e., each arriving mobile must achieve a downlink packet throughput of at least θ_{min} bps in either of the two networks. Several versions of TCP have been proposed in literature for wireless environments. For our purposes we assume that the wireless TCP algorithm operates in *split mode* [19]. In brief, the split mode divides the TCP connection into wireless and wired portions, and acks are generated for both portions separately. Therefore, in our hybrid cell scenario TCP acks are generated separately for the single hop between mobiles and AP or NodeB. It is further assumed that each mobile's or receiver's advertised window W^* is set to 1 in the wireless portion of TCP protocol. This is in fact known to provide the best performance of TCP in a single hop case (see [10, 11] and references therein).
Resource allocation in AP: We assume *saturated resource allocation* in the downlink of AP and NodeB networks. Specifically, this assumption for the AP network means the following. Assume that the AP is *saturated* and has infinitely many packets backlogged in its transmission buffer. In other words, there is always a packet in the AP's transmission buffer waiting to be transmitted to each of the connected mobiles. Now, in a WLAN cell resource allocation to an AP on the downlink is carried out through the contention based DCF (Distributed Coordination Function) protocol. If the AP is saturated for a particular mobile's connection and W^* is set to 1, then this particular mobile can benefit from higher number of transmission opportunities (*TxOPs*) won by the AP for downlink transmission to this mobile (hence higher downlink throughput), than if the AP was not saturated or W^* was not set to 1. Thus with the above assumptions, mobiles can be allocated downlink packet throughputs greater than their QoS requirements of θ_{min} and cell resources in terms of *TxOPs* on the downlink will be maximally utilized.
Resource allocation in NodeB: For the NodeB network the saturated resource allocation assumption has the following elaboration. It is assumed that at any given instant, the NodeB cell resources on downlink are fully utilized resulting in a constant maximum cell load of η_{DL}^{max}. This is analogous to the maximal utilization of *TxOPs* in the AP network discussed in the previous paragraph. With this maximum cell load assumption even if a mobile has a minimum packet throughput requirement of only θ_{min} bps, it can actually be allocated a higher throughput if additional unutilized cell resources are available, so that the cell load is always at its maximum of η_{DL}^{max}. If say a new mobile j arrives and if it is possible to accommodate its connection while maintaining the QoS requirements of the presently connected mobiles (this will be decided by the CAC), then the NodeB will initiate a *renegotiation* of QoS attributes (or bearer attributes) procedure with all the presently connected mobiles. All presently connected mobiles will then be allocated a lower throughput than the one prior to the set-up of mobile j's connection. However, this new lower throughput will still be higher than each mobile's QoS requirement. This kind of a renegotiation of QoS attributes is indeed possible in UMTS and it is one of its special features (see Chapter 7 in [12]). Also note a *major* key point here that the average load per user, η, defined previously in Section 2.2, decreases with increasing number of mobiles connected to the NodeB. Though the total cell load is always at its maximum of η_{DL}^{max}, contribution to this total load from a single mobile (i.e., load per user, η) decreases as more mobiles connect to the NodeB cell. We define $\Delta_d(\eta)$ and $\Delta_i(\eta)$ as the average change in η caused by a new mobile's connection and an already connected mobile's disconnection, respectively. Therefore, when a

new mobile connects the load per user drops from η to $\eta - \Delta_d(\eta)$ and when a mobile disconnects the load per user increases from η to $\eta + \Delta_i(\eta)$.

Power control & location of mobiles in NodeB: In downlink, the inter-cell to intra-cell interference ratio denoted by i_j and the orthogonality factor denoted by α_j are different for each mobile j depending on its location in the NodeB cell. Moreover, the throughput achieved by each mobile is interference limited and depends on the signal to interference plus noise ratio (SINR) received at that mobile. Thus, in the absence of any power control the throughput also depends on the location of mobile in the NodeB cell. We however assume a uniform SINR scenario where closed-loop fast power control is applied in the NodeB cell so that each mobile receives approximately the same SINR (see Section 3.5 in [12]). We therefore assume that all mobiles in the NodeB cell are allocated equal throughputs. This kind of a power control will allocate more power to users far away from the NodeB that are subject to higher path-loss, fading and neighboring cell interference. Users closer to the NodeB will be allocated relatively less power since they are susceptible to weaker signal attenuation. In fact, such a fair throughput allocation can also be achieved by adopting a fair and power-efficient channel dependent scheduling scheme as described in [13]. Now since all mobiles are allocated equal throughputs, it can be said that mobiles arrive at an *average* location in the NodeB cell (see Section 8.2.2.2 in [12]). Therefore all mobiles are assumed to have an identical average inter-cell to intra-cell interference ratio $\bar{i}$ (see Section 8.2.2.2 in [12]) and an identical average orthogonality factor $\bar{\alpha}$ (see Section 8.2.2.2 in [12]).

Justification: The assumption on saturated resource allocation is a standard assumption, usually adopted to simplify modeling of complex network frameworks like those of WLAN and UMTS (see for e.g., [12, 14]). Mobiles in NodeB cell are assumed to be allocated equal throughputs in order to have a comparable scenario to that of an AP cell, in which mobiles are also known to achieve fair and equal throughput allocation (see Section 4.2). Moreover, such fair throughput allocation is known to result in a better delay performance for typical file transfers in UMTS [15]. The assumption of mobiles arriving at an average location in the NodeB cell is essential in order to simplify our MDP formulation. For instance, without this assumption the hybrid network system state will have to include the location of each mobile. This will result in an MDP problem with higher dimensional state space which is known to be analytically intractable and not have an exact solution [18]. We therefore assume mobiles arriving at an average location and seek to compute the optimal association policy more from a network planning and dimensioning point of view.

4.2 Downlink Throughput in 802.11 WLAN AP

We reuse the downlink TCP throughput formula for a mobile in a WLAN from [16]. For completeness, here we briefly mention the network model that has been extensively studied in [16] and then simply restate the throughput expression without going into much details. Each mobile connected to the AP uses the Distributed Coordination Function (DCF) protocol with an RTS/CTS frame exchange before any data-ack frame exchange and each mobile (including the AP) has an equal probability of the channel being allocated to it. The AP does not employ any rate control algorithm and transmits at a fixed PHY data rate of R_{data} bps to all mobiles. With the assumption of W^* being set to 1 (Section 4.1), any mobile will always have a TCP ack waiting to be sent back to the AP with probability 1/2, which is also the probability that it contends for the channel. This is however true only for those versions of TCP that do not use delayed acks. If the AP is always saturated or backlogged, the average number of backlogged mobiles contending for the channel is given by $m_b = 1 + \frac{m_c}{2}$. Based on this assumption and since for any connection an ack is sent by the mobile for every TCP packet received, the downlink TCP throughput of a single mobile is given by Section 3.2 in [16] as,

$$\theta_{AP}(m_c) = \frac{L_{TCP}}{m_c(T_{TCPdata} + T_{TCPack} + 2T_{tbo} + 2T_w)}, \tag{4}$$

where L_{TCP} is the size of TCP packets and $T_{TCPdata}$ and T_{TCPack} are the raw transmission times of a TCP data and a TCP ack packet, respectively. T_{tbo} and T_w denote the mean total

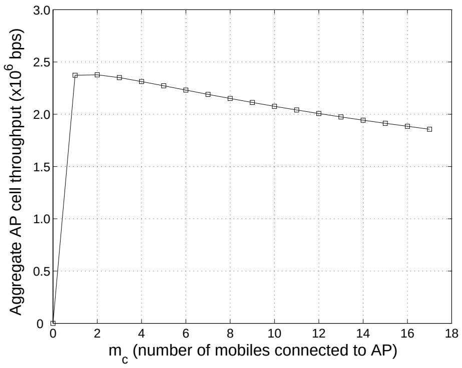

Fig. 2. Throughput of all users in AP cell

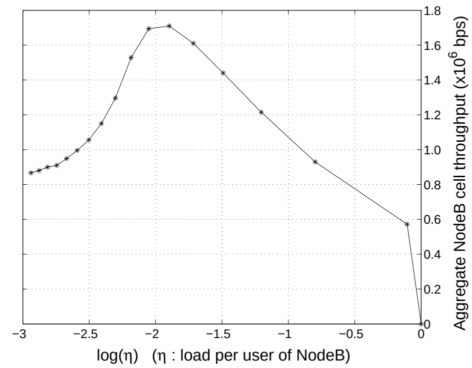

Fig. 3. Throughput of all users in NodeB cell

time spent in *back-off* and the average total time wasted in collisions for any successful packet transmission and are computed assuming m_b backlogged mobiles. The explicit expressions for $T_{TCPdata}$, T_{TCPack}, T_{tbo} and T_w can be referred to in [16]. However, we mention here that they depend on certain quantities whose numerical values have been provided in Section 5.2. Note that all mobiles connected to the AP achieve equal downlink TCP throughputs (given by Equation 4) in a fair manner [16]. Figure 2 shows a plot of *total* cell throughput in an AP cell for an example scenario. Since the total throughput monotonically decreases with increasing number of mobiles, the capacity of an AP cell, M_{AP}, is limited by the QoS requirement θ_{min} bps of each mobile.

4.3 Downlink Throughput in 3G UMTS NodeB

We consider a standard model for data transmission on downlink in a 3G UMTS NodeB cell. Let W be the WCDMA modulation bandwidth and if $SINR$ denotes the signal to interference plus noise ratio received at a mobile then its energy per bit to noise density ratio is given by,

$$\frac{E_b}{N_o} = \frac{W}{\theta_{3G}} \times SINR. \tag{5}$$

Now, under the assumptions of identical throughput allocation to each mobile arriving at an average location and application of power control so that each mobile receives the same SINR (Section 4.1), we deduce from Equation 5 that each mobile requires the same E_b/N_o ratio in order to be able to successfully decode NodeB's transmission. From Chapter 8 in [12] we can thus say that the downlink TCP throughput θ_{3G} of any mobile, in a NodeB cell with saturated resource allocation, as a function of load per user η is given by,

$$\theta_{3G}(\eta) = \frac{\eta W}{(E_b/N_o)(1 - \bar{\alpha} + \bar{i})}, \tag{6}$$

where $\bar{\alpha}$ and $\bar{i}$ have been defined earlier in Section 4.1.

For an example scenario, Figure 3 shows a plot of *total* cell throughput of all mobiles (against $log(\eta)$) in a UMTS NodeB cell. The load per user η has been stretched to a logarithmic scale for better presentation. Also note that throughput values have been plotted in the second quadrant. As we go away from origin on the horizontal axis, $log(\eta)$ (and η) decreases or equivalently number of connected mobiles increase. The equivalence between η and $log(\eta)$ scales and number of mobiles $N(\eta)$ can be referred to in Table 1.

It is to be noted here that the required E_b/N_o ratio by each mobile is a function of its throughput. Also, if the NodeB cell is fully loaded with $\eta_{DL} = \eta_{DL}^{max}$ and if each mobile operates at its minimum throughput requirement of θ_{min} then we can easily compute the capacity, M_{3G}, of the cell as,

$$M_{3G} = \frac{\eta_{DL}^{max} W}{\theta_{min}(E_b/N_o)(1 - \bar{\alpha} + \bar{i})}. \tag{7}$$

η	$log(\eta)$	$N(\eta)$	$SINR$ (dB)	θ_{3G} $(kbps)$	$\frac{E_b}{N_o}$ (dB)
0.9	−0.10536	1	0.8423	572	9.0612
0.45	−0.79851	2	−2.1804	465	6.9503
0.3	−1.204	3	−3.7341	405	5.7894
0.225	−1.4917	4	−5.1034	360	5.0515
0.18	−1.7148	5	−6.0327	322	4.5669
0.15	−1.8971	6	−6.5093	285	4.3052
0.1286	−2.0513	7	−7.2075	242	4.3460
0.1125	−2.1848	8	−8.8312	191	4.7939
0.1	−2.3026	9	−8.9641	144	5.5091
0.09	−2.4079	10	−9.1832	115	6.0281
0.0818	−2.5033	11	−9.9324	96	6.3985
0.0750	−2.5903	12	−10.1847	83	6.6525
0.0692	−2.6703	13	−10.7294	73	6.8625
0.0643	−2.7444	14	−10.9023	65	7.0447
0.06	−2.8134	15	−10.9983	60	7.0927
0.0563	−2.8779	16	−11.1832	55	7.1903
0.0529	−2.9386	17	−11.3802	51	7.2549
0.05	−2.9957	18	−11.9231	47	7.3614

Table 1.

For $\eta_{DL}^{max} = 0.9$, $\theta_{min} = 46$ kbps and a typical NodeB cell scenario that employs the closed-loop fast power control mechanism mentioned previously in Section 4.1, Table 1 shows the SINR (fourth column) received at each mobile as a function of the average load per user (first column). Note that we consider a maximum cell load of 0.9 and not 1 in order to avoid instability conditions in the cell. These values of SINR have been obtained at France Telecom R&D from radio layer simulations of a NodeB cell. The fifth column shows the downlink packet throughput with a block error rate (BLER) of 10^{-2} that can be achieved by each mobile as a function of the SINR observed at that mobile. And the sixth column lists the corresponding values of E_b/N_o ratio (obtained from Equation 5) that are required at each mobile to successfully decode NodeB's transmission.

5 Solving the MDP Control Problem

With the network model defined in previous section, we now solve our MDP formulation of Section 3. As mentioned earlier, the MDP formulation can be solved for any given definition of rewards. Here we will motivate the choice of a particular definition based on aggregate throughput of WLAN and UMTS networks.

5.1 Defining the Rewards and State Evolution

If we consider the global performance of hybrid cell in terms of throughput and financial revenue earned by the network operator, it is natural from the network operator's point of view to maximize both aggregate network throughput and financial revenue. Except for a certain band of values of η (or $log(\eta)$), generally the aggregate throughput of an AP or NodeB cell drops when an additional new mobile connects to it (see Figures 2 & 3). However, the network operator gains some financial revenue from the mobile user at the same time. There is thus a trade-off between revenue gain and the aggregate network throughput which motivates us to formulate an instantaneous, *state dependent*, linear (non-linear can also be considered) reward as follows. The reward consists of the sum of a fixed financial revenue price component and β times an aggregate network throughput component which is state dependent. Here β is an appropriate proportionality constant. When a mobile of the dedicated arrival streams is routed to the corresponding AP or NodeB, it generates a financial revenue of f_{AP} and f_{3G}, respectively. A mobile of the common stream generates a financial revenue of $f_{AP3G\to AP}$ on being routed to the AP and $f_{AP3G\to 3G}$ on being routed to the NodeB. Any mobile that is rejected does not generate any financial revenue. The throughput component of the reward is represented by the aggregate network throughput of the corresponding AP or NodeB network to which a newly arrived mobile connects, taking into account the *change* in the state of the system caused by this new mobile's connection. Whereas, if a newly arrived mobile in a dedicated stream is rejected then the throughput component represents the aggregate network throughput of the corresponding AP or NodeB network, taking into account the *unchanged* state of the system. For a rejected mobile belonging to the common stream, it is the maximum of the aggregate throughputs of the two networks that is considered.

With the foregoing discussion in mind, we may define the instantaneous reward functions R_{AP}, R_{3G} and R_{AP3G} introduced earlier in Section 3 as,

$$R_{AP}(m_c, \eta; a) = \begin{cases} \beta \; m_c \; \theta_{AP}(m_c) & : a = 0 \\ f_{AP} + \beta \; (m_c + 1) \; \theta_{AP}(m_c + 1) & : a = 1, m_c < M_{AP} \\ \beta \; m_c \; \theta_{AP}(m_c) & : a = 1, m_c = M_{AP} \end{cases} \tag{8}$$

$$R_{3G}(m_c, \eta; a) = \begin{cases} \beta \; N(\eta) \; \theta_{3G}(\eta) & : a = 0 \\ f_{3G} + \beta \; N(\eta - \Delta_d(\eta)) \; \theta_{3G}(\eta - \Delta_d(\eta)) & : a = 2, N(\eta) < M_{3G} \\ \beta \; N(\eta) \; \theta_{3G}(\eta) & : a = 2, N(\eta) = M_{3G} \end{cases} \tag{9}$$

$$R_{AP3G}(m_c, \eta; a) = \begin{cases} \max\{\beta \; m_c \; \theta_{AP}(m_c), \beta \; N(\eta) \; \theta_{3G}(\eta)\} & : a = 0 \\ f_{AP3G \to AP} + \beta \; (m_c + 1) \; \theta_{AP}(m_c + 1) & : a = 1, m_c < M_{AP} \\ \beta \; m_c \; \theta_{AP}(m_c) & : a = 1, m_c = M_{AP} \\ f_{AP3G \to 3G} + \beta \; N(\eta - \Delta_d(\eta)) \; \theta_{3G}(\eta - \Delta_d(\eta)) & : a = 2, N(\eta) < M_{3G} \\ \beta \; N(\eta) \; \theta_{3G}(\eta) & : a = 2, N(\eta) = M_{3G} \end{cases} \tag{10}$$

where, $\theta_{AP}(\cdot)$ and $\theta_{3G}(\cdot)$ have been defined earlier in Equations 4 & 6 and $N(\cdot)$ can be obtained from Table 1. Note that the discount factor, γ, has already been incorporated in Equation 3. Also, based on the discussion in Section 4.1 we may define the new states at departure events as,

$$(m_c', \eta) = ((m_c - 1) \vee 0, \eta) \quad \text{and} \quad (m_c, \eta') = (m_c, (\eta + \Delta_i(\eta)) \wedge 0.9), \tag{11}$$

for departures at AP and NodeB, respectively. Additionally, the following entities that were introduced in Section 3 may be defined as, $U_n(m_c, \eta; 0) := V_n(m_c, \eta)$, $U_n(m_c, \eta; 1) := V_n((m_c + 1) \wedge M_{AP}, \eta)$ and $U_n(m_c, \eta; 2) := V_n(m_c, (\eta - \Delta_d(\eta)) \vee 0.05)$ for $\theta_{min} = 46$ kbps (Table 1).

5.2 Numerical Analysis

The focus of our numerical analysis is to study the optimal association policy under an ordinary network scenario. We do not investigate in detail the effects of specific TCP parameters and it is outside the scope of this paper. Plugging Equations 8, 9, 10 & 11 in the Dynamic Programming Equation 3, we solve it for an ordinary scenario using the Value Iteration method [18]. The scenario that we consider is as follows: $L_{TCP} = 8000$ bits (size of TCP packets), $L_{MAC} = 272$ bits, $L_{IPH} = 320$ bits (size of MAC and TCP/IP headers), $L_{ACK} = 112$ bits (size of MAC layer ACK), $L_{RTS} = 180$ bits, $L_{CTS} = 112$ bits (size of RTS and CTS frames), $R_{data} = 11$ Mbits/s, $R_{control} = 2$ Mbits/s (802.11 PHY data transmission and control rates), $CW_{min} = 32$ (minimum 802.11 contention window), $T_P = 144\mu s$, $T_{PHY} = 48\mu s$ (times to transmit the PLCP preamble and PHY layer header), $T_{DIFS} = 50\mu s$, $T_{SIFS} = 10\mu s$ (distributed inter-frame spacing time and short inter-frame spacing time), $T_{slot} = 20\mu s$ (slot size time), $K = 7$ (*retry limit* in 802.11 standard), $b_0 = 16$ (initial mean back-off), $p = 2$ (exponential back-off multiplier), $\gamma = 0.8$, $\lambda_{AP} = 0.03$, $\lambda_{3G} = 0.03$, $\lambda_{AP3G} = 0.01$, $1/\zeta = 10^6$ bits, $\beta = 10^{-6}$, $M_{AP} = 18$ and $M_{3G} = 18$ for $\theta_{min} = 46$ kbps, $\bar{\alpha} = 0.9$ for ITU Pedestrian A channel, $\bar{\imath} = 0.7$, $W = 3.84$ Mcps and other values as illustrated in Table 1.

The DP equation has been solved for three different kinds of network setups. We first study the simple *homogenous* network case where both networks are AP and hence an incoming mobile belonging to the common stream is offered a connection choice between two identical AP networks. Next, we study an analogous case where both networks are NodeB terminals. We study these two cases in order to gain some insight into connection routing dynamics in simple homogenous network setups before studying the third more complex, hybrid AP-NodeB scenario. Figures 4-8 show the optimal connection routing policy for the three network setups.

Note that the plot in Figure 5 is in 3^{rd} quadrant and the plots in Figures 6-8 are in 2^{nd} quadrant. In all these figures a square box symbol (□) denotes routing a mobile's connection to the *first* network, a star symbol ($*$) denotes routing to the *second* network and a cross symbol ($\times$) denotes rejecting a mobile all together.

AP-AP homogenous case: In Figure 4, optimal policy for the common stream in an AP-AP homogenous network setup is shown with $f_{AP1AP2\to AP1} = f_{AP1AP2\to AP2} = 5$ (with some abuse of notation). The optimal policy routes mobiles of common stream to the network which has lesser number of mobiles than the other one. We refer to this behavior as *mobile-balancing* network phenomenon. This happens because the total throughput of an AP network decreases with increasing number of mobiles (Figure 2). Therefore, an AP network with higher number of mobiles offers lesser reward in terms of network throughput and a mobile generates greater incentive by joining the network with fewer mobiles. Also note that the optimal routing policy in this case is *symmetric* and of *threshold type* with the threshold switching curve being the coordinate line $y = x$.

NodeB-NodeB homogenous case: Figure 5 shows optimal routing policy for the common stream in a NodeB-NodeB homogenous network setup. With equal financial incentives for the mobiles, i.e., $f_{3G13G2\to 3G1} = f_{3G13G2\to 3G2} = 5$ (with some abuse of notation), we observe a very interesting switching curve structure. The state space in Figure 5 is divided into an *L-shaped* region (at bottom-left) and a *quadrilateral shaped* region (at top-right) under the optimal policy. Each region separately, is *symmetric* around the coordinate diagonal line $y = x$. Consider the point $(log(\eta_1), log(\eta_2)) = (-0.79851, -1.4917)$ on logarithmic scale in the upper triangle of the quadrilateral region. From Table 1 this corresponds to the network state when load per user in the first NodeB network is 0.45 which is more than the load per user of 0.225 in the second NodeB network. Equivalently, there are less mobiles connected to the first network as compared to the second network. Ideally, one would expect new mobiles to be routed to the first network rather than the second network. However, according to Figure 5 in this state the optimal policy is to route to the second network even though the number of mobiles connected to it is more than those in the first. We refer to this behavior as *mobile-greedy* network phenomenon and explain the intuition behind it in the following paragraph. The routing policies on boundary coordinate lines are clearly comprehensible. On $y = -2.9957$ line when the first network is full (i.e., with least possible load per user), incoming mobiles are routed to second network (if possible) and vice-versa for the line $x = -2.9957$. When both networks are full, incoming mobiles are rejected which is indicated by the cross at coordinate point $(x, y) = (-2.9957, -2.9957)$.

The reason behind the mobile-greedy phenomenon in Figure 5 can be attributed to the fact that in a NodeB network, the total throughput increases with decreasing average load per user up to a particular threshold (say η_{thres}) and then decreases thereafter (see Figure 3). Therefore, routing new mobiles to a network with lesser (but greater than η_{thres}) load per user (greater number of mobiles) results in a higher reward in terms of total network throughput, than routing new mobiles to the other network with greater load per user (lesser number of mobiles). However, the mobile-greedy phenomenon is only limited to the quadrilateral shaped region. In the L-shaped region, the throughput of a NodeB network decreases with decreasing load per user, contrary to the quadrilateral region where the throughput increases with decreasing load per user. Hence, in the L-shaped region higher reward is obtained by routing to the network having higher load per user (lesser number of mobiles) than by routing to the network with lesser load per user (greater number of mobiles). In this sense the L-shaped region shows similar characteristics to mobile-balancing phenomenon observed in AP-AP network setup (Figure 4).

AP-NodeB hybrid cell: We finally discuss now the hybrid AP-NodeB network setup. Here we consider financial revenue gains of $f_{AP3G\to AP} = 5$ and $f_{AP3G\to 3G} = 6$ motivated by the fact that a network operator can charge more for a UMTS connection since it offers a larger coverage area. Moreover, UMTS equipment is more expensive to install and maintain than WLAN equipment. In Figure 6, we observe that the state space is divided into two regions by the optimal policy switching curve which is *neither convex nor concave.* Besides, in some regions of state space the mobile-balancing network phenomenon is observed, where as in some other regions the mobile-greedy network phenomenon is observed. In some sense, this can be attributed to the symmetric

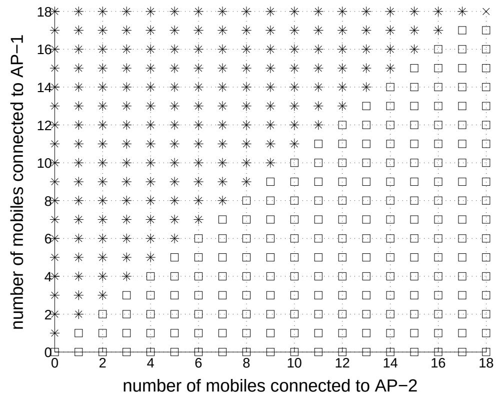

Fig. 4. Optimal policy for common flow in AP-AP setup. *First* network: AP1, *Second* network: AP2.

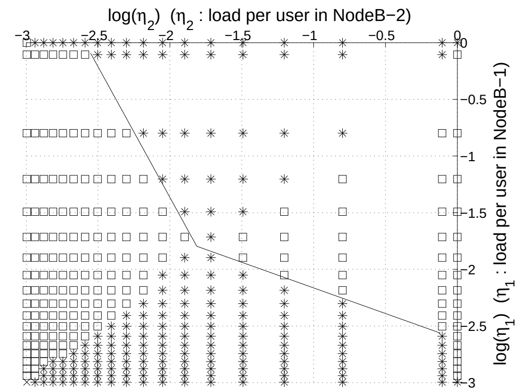

Fig. 5. Optimal policy for common flow in NodeB-NodeB setup. *First* network: NodeB1, *Second* network: NodeB2.

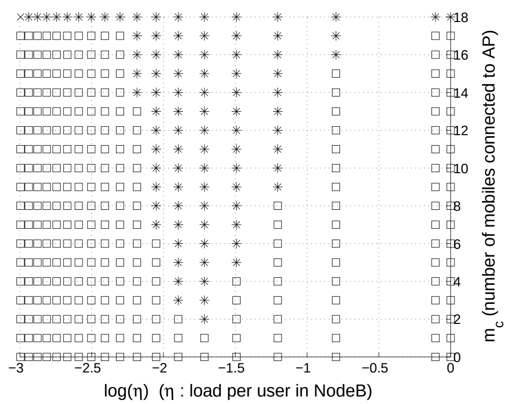

Fig. 6. Optimal policy for common flow in AP-NodeB hybrid cell. *First* network: AP, *Second* network: NodeB.

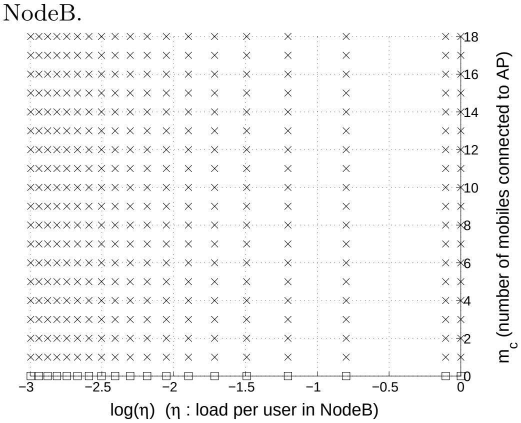

Fig. 7. Optimal policy for AP dedicated flow in AP-NodeB hybrid cell

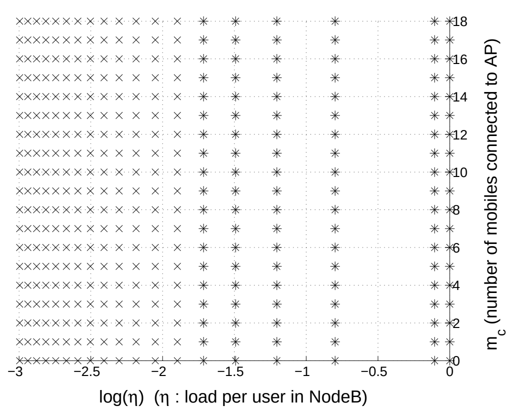

Fig. 8. Optimal policy for NodeB dedicated flow in AP-NodeB hybrid cell

threshold type switching curve and the symmetric L-shaped and quadrilateral shaped regions in the corresponding AP-AP and NodeB-NodeB homogenous network setups, respectively. Figures 7 and 8 show the optimal policies for dedicated streams in an AP-NodeB hybrid cell with $f_{AP} = f_{3G} = 0$. The optimal policy accepts new mobiles in the AP network only when there are none already connected. This happens because initially the network throughput of an AP is zero when there are no mobiles connected and a non-zero reward is obtained by accepting a mobile. Thereafter, since $f_{AP} = 0$ the policy rejects all incoming mobiles due to decrease in network throughput with increasing number of mobiles and hence decrease in corresponding reward. Similarly, for the dedicated mobiles to the NodeB network, the optimal policy accepts new mobiles until the network throughput increases (Figure 3) and rejects them thereafter due to absence of any financial reward component and decrease in the network throughput. Note that we have considered zero financial gains here ($f_{AP} = f_{3G} = 0$) to be able to exhibit existence of these *threshold type* policies for the dedicated streams.

6 Conclusion

In this paper, we have considered globally optimal user-network association (load balancing) in an AP-NodeB hybrid cell. To the best of our knowledge this study is the first of its kind. Since it is infeasible to solve an MDP formulation for an exhaustive set of network scenarios, we have considered an ordinary network scenario and computed the optimal association policy. Even though the characteristics of the solution to our particular scenario are not depictive of the complete solution space, they can certainly be helpful in acquiring an intuition about the underlying dynamics of user-network association in a hybrid cell.

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