

Chapter 2

Decentralized Optimal Resource Allocation

Mutli-homing radio resource allocation is considered to be a promising solution that can efficiently exploit the available resources in a heterogeneous wireless access medium to satisfy required QoS, reduce call blocking probability, and enhance mobility support. The main challenge in designing a multi-homing resource allocation algorithm is how to coordinate the allocation from different networks so as to satisfy the user's target QoS while making efficient utilization of available network resources. One simple solution is to employ a central resource manager with a global view over the available resources and the calls required QoS, that can perform the necessary coordination among different networks. However, this solution is not practical in the case that those different networks are operated by different service providers. Hence, the question now is how to coordinate the resource allocation in different networks without a central resource manager. In addition, it is more practical that every network prioritize resource allocation to its own subscribers as compared to other users. In this chapter, we present a decentralized optimal radio resource allocation mechanism that enables each MT to coordinate the resource allocation from different networks to satisfy its target QoS, and allows each network to give a higher priority in allocating its resources to its own subscribers. We first present the system model under consideration, then discuss the problem formulation for the decentralized resource allocation.

2.1 System Model

2.1.1 Wireless Access Networks

Consider a geographical region with a set \mathcal{N} of available wireless access networks, $\mathcal{N} = \{1, 2, \dots, N\}$. Each network, $n \in \mathcal{N}$, is operated by a unique service provider and has a set, \mathcal{S}_n , of BSs/APs in the geographical region with $\mathcal{S}_n = \{1, 2, \dots, S_n\}$. The BSs/APs of different networks have different coverage that overlaps in some

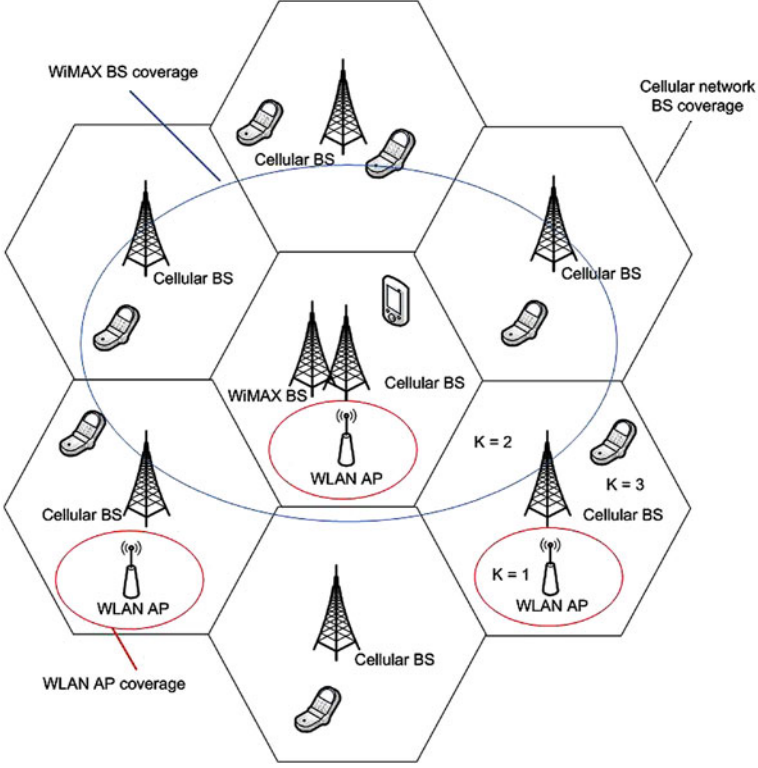


Fig. 2.1 The networks coverage areas

areas. Hence, the geographical region is partitioned to a set \mathcal{K} of service areas, $\mathcal{K} = \{1, 2, \dots, K\}$. As shown in Fig. 2.1, each service area $k \in \mathcal{K}$ is covered by a unique subset of networks BSs/APs. Each BS/AP, $s \in \mathcal{S}_n$ for $n \in \mathcal{N}$, has a downlink transmission capacity of C_n Mbps.

2.1.2 Network Subscribers and Users

There are M MTs with multiple radio interfaces and multi-homing capabilities in the geographical region, given by the set $\mathcal{M} = \{1, 2, \dots, M\}$. Each MT has its own home network but can also get service from other available networks. Let $\mathcal{M}_{ns} \subset \mathcal{M}$ denote the set of MTs which lie in the coverage area of the s th BS/AP of the n th network. The set \mathcal{M}_{ns} is further divided into two subsets, \mathcal{M}_{ns1} to denote MTs whose home network is network n , and \mathcal{M}_{ns2} to denote MTs whose home network is not network n . Hence, $\mathcal{M}_{ns1} \cup \mathcal{M}_{ns2} = \mathcal{M}_{ns}$, and $\mathcal{M}_{ns1} \cap \mathcal{M}_{ns2} = \emptyset$. An MT

$m \in \mathcal{M}_{ns1}$ is referred to as network n subscriber, while an MT $m \in \mathcal{M}_{ns2}$ is referred to as network n user.

2.1.3 Service Requests

The MTs service requests are expressed in terms of call required bandwidth. An MT can receive its required bandwidth from all available wireless access networks using its multi-homing capability. The allocated bandwidth from network n to an MT m through BS/AP s in the downlink is given by b_{nms} , with $n \in \mathcal{N}$, $m \in \mathcal{M}_{ns}$, and $s \in \mathcal{S}_n$. Let B be a matrix of bandwidth allocation from each network n through BS/AP s to each MT m , $B = [b_{nms}]$, $n \in \mathcal{N}$, $m \in \mathcal{M}$, $s \in \mathcal{S}_n$, with $b_{nms} = 0$ if MT m is not in the coverage area of network n BS/AP s . It should be noted that, while we study bandwidth allocation in the downlink, the same framework can be applied for bandwidth allocation in the uplink.

The networks support both CBR and VBR services. An MT, m , with a CBR call requires a constant bandwidth B_m from all wireless access networks available at its location. On the other hand, an MT, m , with a VBR call requires a bandwidth allocation within a maximum value B_m^{\max} and a minimum value B_m^{\min} . With sufficient available radio resources, the VBR call is allocated its maximum required bandwidth B_m^{\max} . When all networks BSs/APs reach their transmission capacity limitation C_n , the allocated bandwidth for the VBR call is degraded towards B_m^{\min} in order to support more calls. Let \mathcal{M}_{r1} denotes the set of MTs in the geographical region with CBR service, while \mathcal{M}_{r2} denotes the set of MTs in the geographical region with VBR service, and both are a subset of \mathcal{M} .

We consider call-level radio resource allocation. The radio resource allocation mechanism is to find the optimal resource allocation to a set of MTs in a particular service area from each of the available BSs/APs. As a first step, the resource allocation is performed according to the average call level statistics in different service areas [39]. Hence, a static system is investigated without arrivals of new calls or departures of existing ones. It is assumed that a call admission control procedure is in place [60], and a feasible resource allocation solution exists.

2.2 Formulation of the Radio Resource Allocation Problem

In this section, we discuss the problem formulation of radio resource allocation for a static system of multi-homing MTs in the heterogeneous wireless access medium. A decentralized solution for the problem is then presented based on the problem formulation.

The utility $u_m(b_{nms})$ of network n allocating bandwidth b_{nms} to MT m through BS/AP s is given by

$$u_{nms}(b_{nms}) = \ln(1 + \eta_1 b_{nms}) - \eta_2(1 - p_{nms})b_{nms} \quad (2.1)$$

where η_1 and η_2 are used for scalability of b_{nms} [57], and $p_{nms} \in [0, 1]$ is a priority parameter set by network n BS/AP s on its resources for MT m . The attained network utility from the allocated bandwidth is a concave function of b_{nms} [6] and is given by the first term in the right hand side of (2.1) [39]. The cost that the user pays for the allocated bandwidth is given by the second term in the right hand side of (2.1). This term is a linear function of the allocated bandwidth b_{nms} ; hence, the more the allocated bandwidth, the higher the cost. The utility function of (2.1) involves a trade-off between the attained network utility and the cost that the user pays on the network radio resources [28]. The utility function of (2.1) is a concave function of the allocated bandwidth b_{nms} [6]. We employ priority parameter p_{nms} set by network n BS/AP s to MT m to establish service differentiation among different users, which is given by

$$p_{nms} = \begin{cases} 1, & \forall m \in \mathcal{M}_{ns1} \\ \beta, & \forall m \in \mathcal{M}_{ns2} \end{cases} \quad (2.2)$$

where $\beta \in [0, 1)$. Using (2.2) in (2.1), the utility function for a network subscriber accounts only on the attained network utility by that subscriber, while a network user suffers from a trade-off between the attained network utility and the cost that the network sets on its resources [28]. This enables each network to give a higher priority in allocating its resources to its own subscribers than to other users. The allocated bandwidth to MTs with VBR service is reduced, when all networks in the geographical region reach their capacity limitation, in order to support more calls. However, each subscriber should be able to enjoy the resources of its own home network. Hence, it is desirable to differentiate the radio resource allocation performed by a network to its own subscribers and the allocation performed by that network to the other users. This is taken care of by the priority parameter p_{nms} which gives a higher cost on the network resources for the network users than to the network subscribers. Each network, $n \in \mathcal{N}$, assigns a priority parameter value $p_{nms} \in [0, 1)$ on its resources for the users in its coverage area, while setting $p_{nms} = 1$ for its own subscribers. Hence, the subscribers of each network with VBR service enjoy their maximum required bandwidth using their home network radio resources. A network degrades its resource allocation to its own subscribers only so as not to violate the minimum required bandwidth of the other users.

The radio resource allocation objective of each network BS/AP is to maximize the total satisfaction for all MTs that lie within its coverage area, which is given by

$$U_{ns} = \sum_{m \in \mathcal{M}_{ns}} u_{nms}(b_{nms}), \quad \forall s \in \mathcal{S}_n, n \in \mathcal{N} \quad (2.3)$$

where U_{ns} is the total utility of network n BS/AP s .

The overall radio resource allocation objective of all networks in the geographical region is to find the optimal bandwidth allocation b_{nms} , $\forall n \in \mathcal{N}$, $\forall m \in \mathcal{M}$, $\forall s \in \mathcal{S}_n$, which maximizes the total utility in the region, given by

$$U = \sum_{n=1}^N \sum_{s=1}^{S_n} U_{ns}. \quad (2.4)$$

The total bandwidth allocation by each network n BS/AP s should be such that the total call traffic load in its coverage area is within the network BS/AP transmission capacity limitation C_n , that is

$$\sum_{m \in \mathcal{M}_{ns}} b_{nms} \leq C_n, \quad \forall s \in \mathcal{S}_n, n \in \mathcal{N}. \quad (2.5)$$

For an MT with CBR service, the total bandwidth allocation from all available wireless access networks to this MT should satisfy its application required bandwidth, that is

$$\sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms} = B_m, \quad \forall m \in \mathcal{M}_{r1}. \quad (2.6)$$

As for an MT with VBR service, the total bandwidth allocation from all available wireless access networks to this MT should be within the application minimum required bandwidth B_m^{\min} and the application maximum required bandwidth B_m^{\max} , that is

$$B_m^{\min} \leq \sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms} \leq B_m^{\max}, \quad \forall m \in \mathcal{M}_{r2}. \quad (2.7)$$

Hence, the radio resource allocation for MTs with multi-homing capabilities in the heterogeneous wireless access medium, for CBR and VBR services, can be expressed by the following optimization problem

$$\begin{aligned} & \max_{B \geq 0} \quad U \\ & \text{s.t.} \quad (2.5) - (2.7). \end{aligned} \quad (2.8)$$

Using the utility function definitions in (2.1), (2.3), and (2.4), the objective function of (2.8) is concave and the problem has linear constraints. Therefore, problem (2.8) is a convex optimization problem, and a local maximum is a global maximum as well [6]. Although problem (2.8) can be solved efficiently in polynomial time complexity in a centralized manner using a central resource manager, this is not practical in a case that these networks are operated by different service providers. Thus, it is desirable to develop a decentralized solution of (2.8).

Constraints (2.6) and (2.7) are coupling constraints that make it difficult to obtain the desirable decentralized solution of (2.8) at each network. A decentralized solution can be developed using full dual decomposition of (2.8) [15, 30, 32, 49, 50]. We can rewrite constraint (2.7) in the following form

$$\sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms} \leq B_m^{\max}, \quad \forall m \in \mathcal{M}_{r2} \quad (2.9)$$

$$\sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms} \geq B_m^{\min}, \quad \forall m \in \mathcal{M}_{r2}. \quad (2.10)$$

In order to develop the decentralized solution, first we find the Lagrangian function for (2.8) using constraints (2.9) and (2.10), which can be expressed as

$$\begin{aligned} L(B, \lambda, v, \mu^{(1)}, \mu^{(2)}) = & \sum_{n=1}^N \sum_{s=1}^{S_n} U_{ns} + \sum_{n=1}^N \sum_{s=1}^{S_n} \lambda_{ns} \left(C_n - \sum_{m \in \mathcal{M}_{ns}} b_{nms} \right) \\ & + \sum_{m \in \mathcal{M}_{r1}} v_m \left(B_m - \sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms} \right) \\ & + \sum_{m \in \mathcal{M}_{r2}} \mu_m^{(1)} \left(B_m^{\max} - \sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms} \right) \\ & + \sum_{m \in \mathcal{M}_{r2}} \mu_m^{(2)} \left(\sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms} - B_m^{\min} \right) \end{aligned} \quad (2.11)$$

with $\lambda = (\lambda_{ns} : n \in \mathcal{N}, s \in \mathcal{S}_n)$ defined to be a matrix of Lagrange multipliers corresponding to capacity constraint (2.5), and $\lambda_{ns} \geq 0$, $v = (v_m : m \in \mathcal{M}_{r1})$, $\mu^{(1)} = (\mu_m^{(1)} : m \in \mathcal{M}_{r2})$, $\mu^{(2)} = (\mu_m^{(2)} : m \in \mathcal{M}_{r2})$ are vectors of lagrange multipliers corresponding to the required bandwidth constraints (2.6), (2.9), and (2.10) respectively, and $\mu_m^{(1)}, \mu_m^{(2)} \geq 0$. The dual function is given by

$$h(\lambda, v, \mu^{(1)}, \mu^{(2)}) = \max_{B \geq 0} L(B, \lambda, v, \mu^{(1)}, \mu^{(2)}) \quad (2.12)$$

and the dual problem corresponding to the primal problem (2.8) is expressed by

$$\min_{(\lambda, \mu^{(1)}, \mu^{(2)}) \geq 0, v} h(\lambda, v, \mu^{(1)}, \mu^{(2)}). \quad (2.13)$$

A strong duality holds since the optimization problem (2.8) is a convex optimization problem, which makes the optimal values for the primal and dual problems equal [6]. The maximization problem (2.12) can be written as

$$h(\lambda, \nu, \mu^{(1)}, \mu^{(2)}) = \sum_{n=1}^N \sum_{s=1}^{S_n} \max_{B \geq 0} \left\{ U_{ns} - \lambda_{ns} \sum_{m \in \mathcal{M}_{ns}} b_{nms} - \sum_{m \in \mathcal{M}_{r1}} \nu_m b_{nms} - \sum_{m \in \mathcal{M}_{r2}} (\mu_m^{(1)} - \mu_m^{(2)}) b_{nms} \right\}. \quad (2.14)$$

Then, each network BS/AP can solve its own network utility maximization (NUM) problem, given by

$$\max_{B \geq 0} \left\{ U_{ns} - \lambda_{ns} \sum_{m \in \mathcal{M}_{ns}} b_{nms} - \sum_{m \in \mathcal{M}_{r1}} \nu_m b_{nms} - \sum_{m \in \mathcal{M}_{r2}} (\mu_m^{(1)} - \mu_m^{(2)}) b_{nms} \right\}. \quad (2.15)$$

By applying the Karush-Kuhn-Tucker (KKT) conditions on (2.15), each network BS/AP can find the bandwidth allocation, b_{nms} , for fixed values of λ , ν , $\mu^{(1)}$, and $\mu^{(2)}$. Thus, we have

$$\frac{\partial U_{ns}}{\partial b_{nms}} - \lambda_{ns} - \nu_m - (\mu_m^{(1)} - \mu_m^{(2)}) = 0 \quad (2.16)$$

which results in

$$b_{nms} = \left[\left(\frac{\eta_1}{\lambda_{ns} + \nu_m + \eta_2(1 - p_{nms})} - 1 \right) / \eta_1 \right]^+, \quad \forall m \in \mathcal{M}_{r1} \quad (2.17)$$

$$b_{nms} = \left[\left(\frac{\eta_1}{\lambda_{ns} + (\mu_m^{(1)} - \mu_m^{(2)}) + \eta_2(1 - p_{nms})} - 1 \right) / \eta_1 \right]^+, \quad \forall m \in \mathcal{M}_{r2} \quad (2.18)$$

where the notion $[\cdot]^+$ is a projection on the positive quadrature to account for the fact that $B \geq 0$. By solving the dual problem (2.13), we can obtain the optimal values for the Lagrange multipliers that results in the optimal bandwidth allocation b_{nms} of (2.17) and (2.18). For a fixed bandwidth allocation B , the dual problem can be written as

$$\begin{aligned} & \sum_{n=1}^N \sum_{s=1}^{S_n} \min_{\lambda \geq 0} \left\{ \lambda_{ns} \left(C_n - \sum_{m \in \mathcal{M}_{ns}} b_{nms} \right) \right\} + \sum_{m \in \mathcal{M}_{r1}} \min_{\nu} \left\{ \nu_m \left(B_m - \sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms} \right) \right\} \\ & + \sum_{m \in \mathcal{M}_{r2}} \min_{\mu^{(1)} \geq 0} \left\{ \mu_m^{(1)} \left(B_m^{\max} - \sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms} \right) \right\} \\ & + \sum_{m \in \mathcal{M}_{r2}} \min_{\mu^{(2)} \geq 0} \left\{ \mu_m^{(2)} \left(\sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms} - B_m^{\min} \right) \right\}. \end{aligned} \quad (2.19)$$

For a differentiable dual function, a gradient descent method can be applied so as to find the optimal values for the Lagrangian multipliers [6], which is given by

$$\lambda_{ns}(i+1) = \left[\lambda_{ns}(i) - \alpha_1 \left(C_n - \sum_{m \in \mathcal{M}_{ns}} b_{nms}(i) \right) \right]^+ \quad (2.20)$$

$$v_m(i+1) = v_m(i) - \alpha_2 \left(B_m - \sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms}(i) \right) \quad (2.21)$$

$$\mu_m^{(1)}(i+1) = \left[\mu_m^{(1)}(i) - \alpha_3 \left(B_m^{\max} - \sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms}(i) \right) \right]^+ \quad (2.22)$$

$$\mu_m^{(2)}(i+1) = \left[\mu_m^{(2)}(i) - \alpha_4 \left(\sum_{n=1}^N \sum_{s=1}^{S_n} b_{nms}(i) - B_m^{\min} \right) \right]^+ \quad (2.23)$$

where i is an iteration index and α_j , $j = \{1, 2, 3, 4\}$, is a fixed sufficiently small step size. As the gradient of (2.19) satisfies the Lipchitz continuity condition, the convergence of (2.20)–(2.23) towards the optimal solution is guaranteed [6]. Hence, the radio resource allocation b_{nms} of (2.17) and (2.18) converges to the optimal solution.

2.3 A Decentralized Optimal Resource Allocation (DORA) Algorithm

The decomposition approach for optimization problem (2.8) is defined in two levels. The first one is a lower level that is executed at each network, $n \in \mathcal{N}$, BS/AP, $s \in \mathcal{S}_n$, so as to find the optimal radio resource allocation b_{nms} for each MT $m \in \mathcal{M}_{ns}$. This optimal resource allocation is found by solving the sub-problems given in (2.15) by BSs/APs, which results in the solution of (2.17) for MTs with CBR service and (2.18) for MTs with VBR service. The other is a higher level, where the master problem is solved. The master problem is given in (2.19) and its optimal solution is obtained using the iterative method introduced in (2.20)–(2.23). The role of the master problem is to set the dual variables λ , v , $\mu^{(1)}$ and $\mu^{(2)}$ so as to coordinate the sub-problems solution at each network BS/AP. This is illustrated in Fig. 2.2.

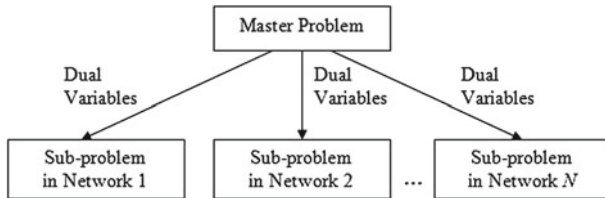


Fig. 2.2 Decomposition of problem (2.8)

Following the classical interpretation of λ_{ns} in economics as the resource price [32], we refer to λ_{ns} as the link access price for network n BS/AP s . Basically, λ_{ns} serves as an indication of the capacity limitation experienced by network n link resources in BS/AP s . Hence, when the total call traffic load in network n BS/AP s ($\sum_{m \in \mathcal{M}_{ns}} b_{nms}$) reaches the capacity limitation (C_n), the link access price (λ_{ns}) increases to denote that it is expensive to use that link. The rest of the Lagrangian multipliers, namely v_m which is used by MTs with CBR service, and $\mu_m^{(1)}$ and $\mu_m^{(2)}$ which are used by MTs with VBR service, are coordination parameters. Hence, v_m is used by MT m to coordinate the allocations by the available BSs/APs so as to ensure that the required bandwidth B_m is met. Similarly, $\mu_m^{(1)}$ and $\mu_m^{(2)}$ are used by MT m to coordinate the BS/AP resource allocations of different networks so as to ensure that the allocated resources lie within the specified required bandwidth range $[B_m^{\min}, B_m^{\max}]$.

The link access price λ_{ns} is calculated at each network BS/AP according to its capacity limitation and the total call traffic load experienced by the BS/AP. The coordination parameter v_m is calculated at each MT with CBR service, while the coordination parameters $\mu_m^{(1)}$ and $\mu_m^{(2)}$ are calculated by each MT with VBR service. All coordination parameters are calculated based on the allocated bandwidth from different wireless access networks and the MT required bandwidth. The decentralized optimal radio resource allocation (DORA) algorithm can be explained using the scenario given in Fig. 2.3. Consider an MT which lies in the coverage area of a WLAN AP and cellular network and WiMAX BSs. Each BS/AP defines an initial feasible value for its link access price λ_{ns} . Similarly, the MT defines an initial feasible value for its coordination parameter(s). Each BS/AP performs its bandwidth allocation to the MT based on the network BS/AP link access price, the MT priority parameter and its coordination parameter values. Each BS/AP then updates its link access price value based on its capacity limitation and its experienced total call traffic load (due to the previous iteration resource allocation). Also, the MT updates its coordination parameter(s) (v_m for MT with CBR service and $\mu_m^{(1)}$ and $\mu_m^{(2)}$ for MT with VBR service) based on the difference between its required bandwidth and the previous iteration total resource allocation. The updated coordination parameter for the new iteration (v_m or the difference $\mu_m^{(1)} - \mu_m^{(2)}$) is broadcasted by the MT to the different available wireless access networks through the MT different radio interfaces so as to coordinate the resource allocation from different networks. As a result, each BS/AP can update its bandwidth allocation to the MT (using the updated link access price and coordination parameter values). The process continues over a number of iterations until the MT required bandwidth can be met eventually.

The detailed (DORA) algorithm is given in Table 2.1, where ψ is a small tolerance.

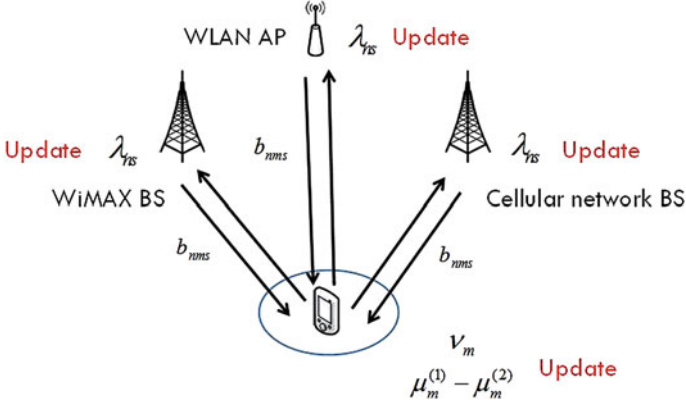


Fig. 2.3 Decentralized radio resource allocation

2.4 Numerical Results and Discussion

This section presents numerical results for the radio resource allocation problem (2.8) using the DORA algorithm given in Table 2.1. We consider a simplified system model with a geographical region that is entirely covered by an IEEE 802.16e WiMAX BS and partially covered by a 3G cellular network BS and an IEEE 802.11b WLAN AP [39], as shown in Fig. 2.4. Thus, $\mathcal{N} = \{1, 2, 3\}$, with the WiMAX, cellular network, and WLAN indexed as 1, 2, and 3 respectively. Each network has only one BS/AP in the geographical region, i.e. $S_n = \{1\}$, $\forall n \in \mathcal{N}$. As a result, the geographical region is described by three service areas, $\mathcal{K} = \{1, 2, 3\}$. In service area 1, only the WiMAX BS coverage is available. In service area 2, both the WiMAX and cellular network coverages are available. In service area 3, all three networks are available. The transmission capacities of the three networks are given by $C_1 = 20$ Mbps, $C_2 = 2$ Mbps, and $C_3 = 11$ Mbps.

For the priority mechanism, different networks can set different costs on their resources through the priority parameter p_{nms} . As the cellular network has the lowest transmission capacity among all the available networks, it sets the highest cost on its resources so as to devote them to its own subscribers. Both the WiMAX and WLAN

M_{331} . On the other hand, the WLAN AP increases its total allocated bandwidth with M_{331} so as to accommodate more subscribers. The WLAN AP reaches its capacity limitation at $M_{331} = 14$.

In the following results, we study the total allocated bandwidth from each network BS/AP to subscribers of different networks in all three service areas.

Figure 2.6a shows the total allocated bandwidth by each network BS/AP for the CBR WLAN subscribers in service area 3. Because of the priority mechanism, the WLAN AP supports its own subscribers with all their required bandwidth in order to avoid the associated high cost of the BSs resources of WiMAX and cellular network. Hence, The bandwidth allocation for the WLAN subscribers from the WiMAX (M-L) and cellular network (C-L) BSs is equal to zero, while the WLAN AP allocated bandwidth (L-L) increases with M_{331} so as to accommodate more subscribers. For $M_{331} > 34$, there is no sufficient resources at the WLAN AP to support individ-

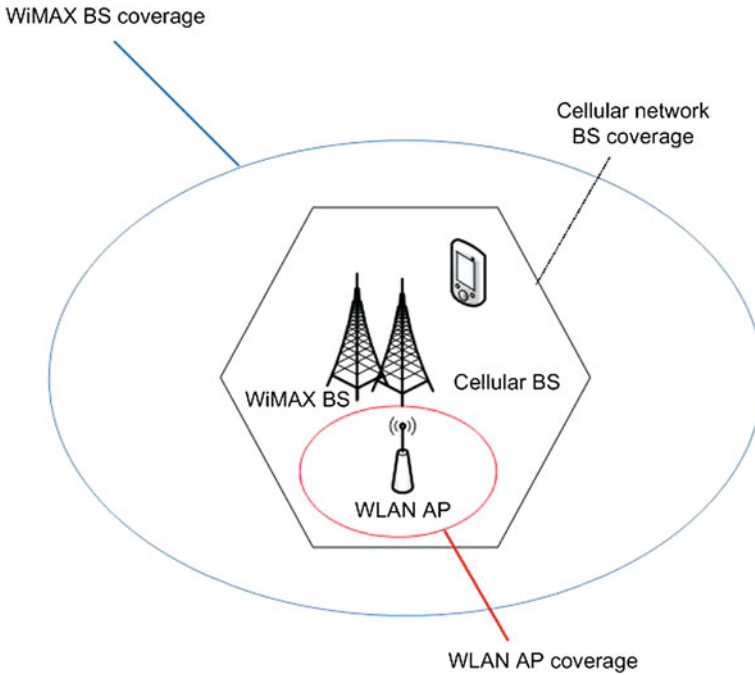


Fig. 2.4 Service areas under consideration

Table 2.2 Number of subscribers of different networks in different service areas

| Parameter | Value | Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|-----------|----------|
| M_{111} | 10 | M_{122} | 7 | M_{221} | 8 | M_{232} | 5 |
| M_{112} | 10 | M_{131} | 5 | M_{222} | 8 | M_{332} | 5 |
| M_{121} | 7 | M_{132} | 5 | M_{231} | 5 | M_{331} | Variable |

ually its own subscribers. Hence, the WiMAX BS increases its bandwidth allocation to support the WLAN subscribers. The support comes only from the WiMAX BS as it sets a lower cost on its resources than the cellular network BS.

Figure 2.6b shows the allocated bandwidth by each network BS/AP for the VBR WLAN subscribers in service area 3. For $M_{331} \geq 22$, the WLAN AP decreases its allocated bandwidth to the VBR subscribers (L-L) in order to support the increasing number of the CBR subscribers. This is compensated by an increase in the bandwidth allocation from the WiMAX BS (M-L) in order to keep the total bandwidth allocation constant at the call maximum required bandwidth (512 Kbps for each VBR call). For $M_{331} > 27$, any further increase in the bandwidth allocation from the WiMAX BS to the WLAN subscribers would degrade the WiMAX BS bandwidth allocation to its own VBR subscribers. This is not allowed, however, by the priority mechanism as it gives higher priority on the WiMAX BS resources to the WiMAX subscribers. Hence, the WiMAX BS decreases its allocated bandwidth to the VBR WLAN subscribers which reduces the VBR call total bandwidth allocation towards the call minimum required bandwidth. For $M_{331} > 34$, the WLAN AP decreases its bandwidth allocation to its VBR subscribers in order to support the increasing number of its CBR subscribers. Hence, the WiMAX BS increases its bandwidth allocation to the WLAN VBR subscribers so as not to violate their minimum required bandwidth (256 Kbps for each VBR call).

Figure 2.7a shows the total allocated bandwidth by each network BS/AP to the cellular network subscribers, with CBR and VBR calls, in service area 3. The total allocated bandwidth of CBR cellular network subscribers (C-CBR Total) comes from

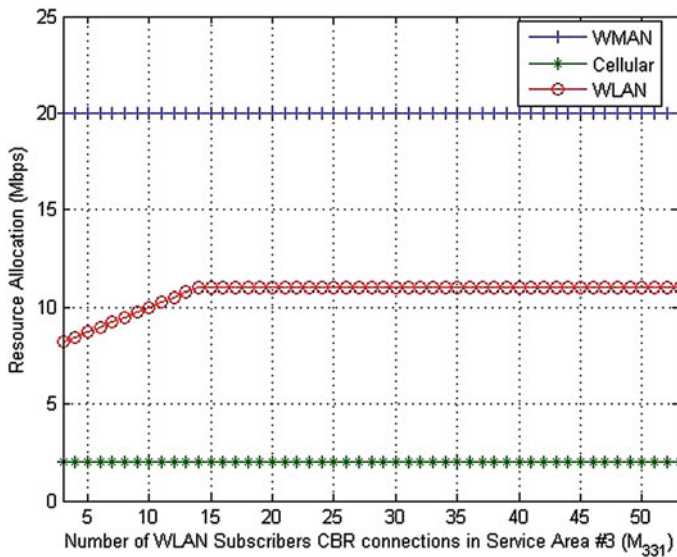


Fig. 2.5 Total bandwidth allocation by each network BS/AP

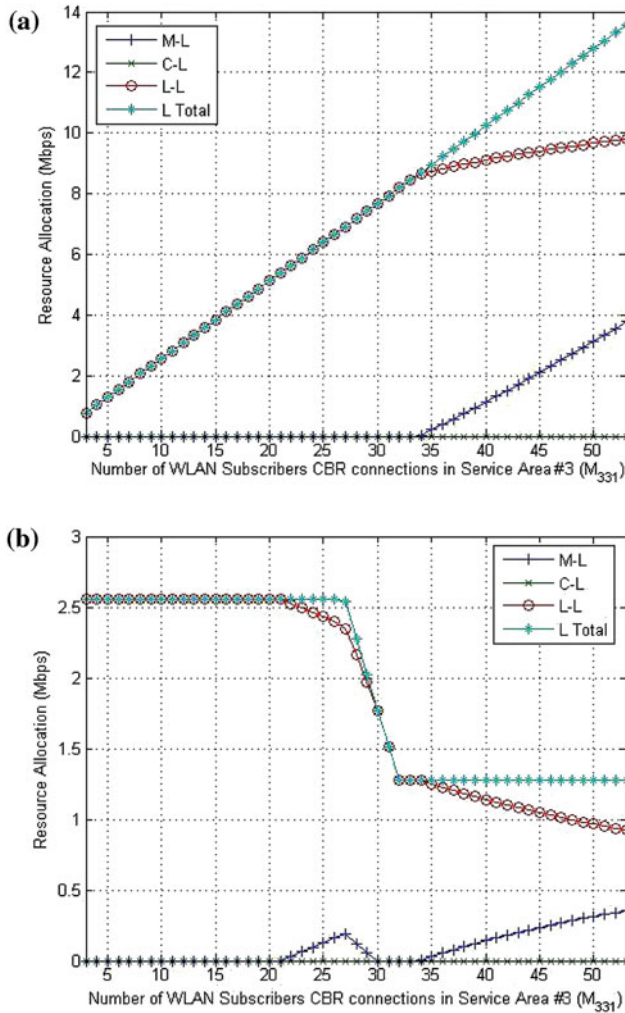


Fig. 2.6 Total bandwidth allocation by each network BS/AP to **a** CBR and **b** VBR WLAN subscribers

the WLAN AP (L-C-CBR). The allocated bandwidth from the cellular network BS (C-C-CBR) is zero, as it uses its bandwidth to support its own subscribers in service area 2 (which is covered only by the cellular network BS, and the WiMAX BS with a higher cost for bandwidth). As for the WiMAX BS zero bandwidth allocation (M-C-CBR), it is due to the higher cost that the WiMAX BS sets on its resources as compared to the WLAN AP. For $M_{331} > 18$, the WLAN AP decreases its bandwidth allocation to the CBR cellular network subscribers in order to support its increasing number of subscribers (M_{331}). Hence, the WiMAX BS increases its allocation to the CBR cellular network subscribers in order to keep the total bandwidth allocation

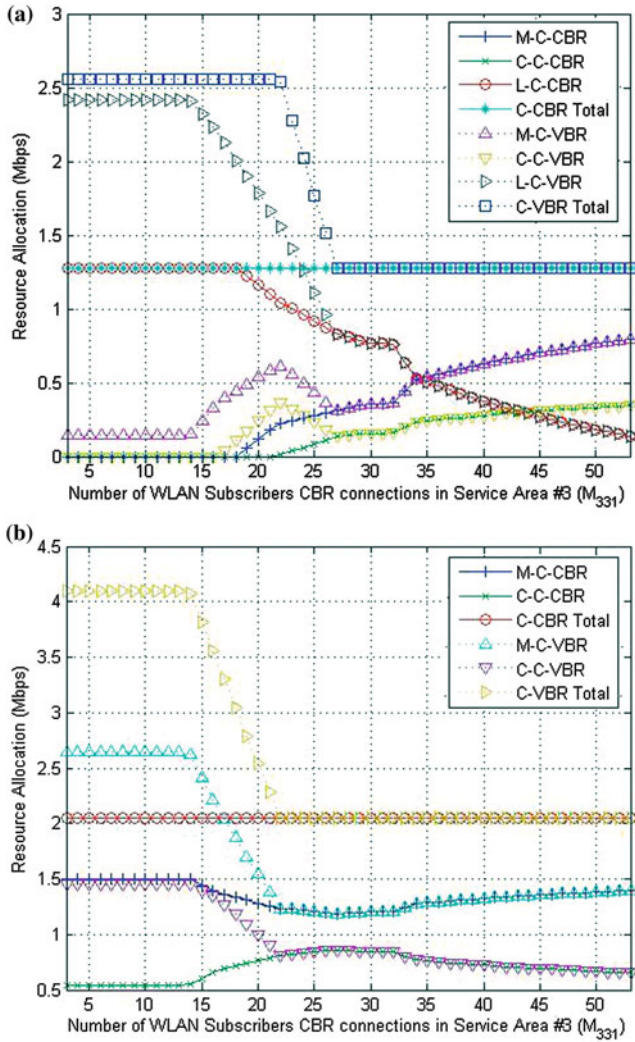


Fig. 2.7 Total bandwidth allocation by each network BS/AP to the cellular network subscribers in **a** Area 3 and **b** Area 2

constant at the required bandwidth (256 Kbps for each CBR call). For $M_{331} > 21$, more allocated bandwidth is required from the WiMAX BS to keep the CBR cellular network subscriber total allocation constant; however, this would increase the associated cost due to the WiMAX BS low priority parameter for the network users. Hence, the cellular network BS increases its allocated bandwidth to support its own CBR subscribers. As shown in the figure, the total bandwidth allocation is always constant at the call required bandwidth. For the VBR subscribers, the WLAN AP decreases its bandwidth allocation to the VBR cellular network subscribers with M_{331} in order to

support its own subscribers. This is compensated for by an increase in the WiMAX BS bandwidth allocation to keep the total allocated bandwidth (C-VBR-Total) at its maximum required bandwidth (512 Kbps for each VBR call). For $M_{331} > 17$, the cellular network BS increases its bandwidth allocation to its VBR subscribers in order to reduce the amount of required bandwidth from the WiMAX BS due to the associated high cost. For $M_{331} > 22$, any further increase in the allocated bandwidth from the WiMAX BS to the VBR cellular network subscribers would reduce the WiMAX BS allocation to its own VBR subscribers. Hence, the WiMAX BS decreases its allocated bandwidth to the VBR cellular network subscribers. Also, the cellular network BS decreases its allocated bandwidth to its VBR subscribers to support its CBR subscribers in this area. As a result, the total allocated bandwidth to the VBR cellular network subscribers starts to decrease towards the minimum required bandwidth. For $M_{331} > 26$, the WiMAX and cellular network BSs increase their bandwidth allocation to the VBR cellular network subscribers in order to compensate for the reduction in the allocated bandwidth from the WLAN AP and keep the total bandwidth allocation constant at the call minimum required bandwidth.

Figure 2.7b shows the total allocated bandwidth by each network BS/AP to the cellular network subscribers in service area 2. The allocated bandwidth comes only from the WiMAX and cellular network BSs since the MTs are out of the coverage area of the WLAN AP. For the CBR subscribers with $M_{331} > 14$, the WiMAX BS reduces its allocated bandwidth to the CBR cellular network subscribers to support its own subscribers with their maximum required bandwidth. As a result, the cellular network BS increases its allocated bandwidth. For $M_{331} > 32$, the cellular network BS reduces its bandwidth allocation to support its subscribers in area 3 (refer to Fig. 2.7a). This is compensated for by an increase in the WiMAX BS allocated bandwidth to the CBR cellular network subscribers. In all the cases, the total bandwidth allocation (C-CBR Total) is constant at the required bandwidth (256 kbps for each CBR user). For the VBR subscribers with $M_{331} > 14$, the cellular network BS cannot further keep its VBR subscribers in area 2 at their maximum required bandwidth, and has to decrease its allocated bandwidth to support the CBR cellular network subscribers in this area. Also, the WiMAX BS has to decrease its bandwidth allocation to satisfy its own VBR subscribers with their maximum required bandwidth. Therefore, the total bandwidth allocation (C-VBR Total) starts to decrease towards the minimum required bandwidth. As in the CBR bandwidth allocation, for $M_{331} > 32$, the cellular network BS reduces its allocated bandwidth to its VBR subscribers in area 2 to support its subscribers in area 3. As a result, the WiMAX BS increases its bandwidth allocation to keep the total allocated bandwidth constant at the minimum required bandwidth.

Figure 2.8a shows the total allocated bandwidth by each network BS/AP to the WiMAX subscribers in service area 3. For both CBR and VBR calls, most of the allocated bandwidth comes from the WiMAX BS (M-M-CBR and M-M-VBR), so as to reduce the associated cost of the WLAN bandwidth allocation. The allocated bandwidth from the cellular network BS (C-M-CBR and C-M-VBR) is zero, as it allocates radio resources to its own subscribers in service areas 2 and 3. For $M_{331} > 13$, the WLAN AP decreases its allocated bandwidth to the VBR WiMAX subscribers in order to support its own subscribers. Hence, the WiMAX BS increases its allocated

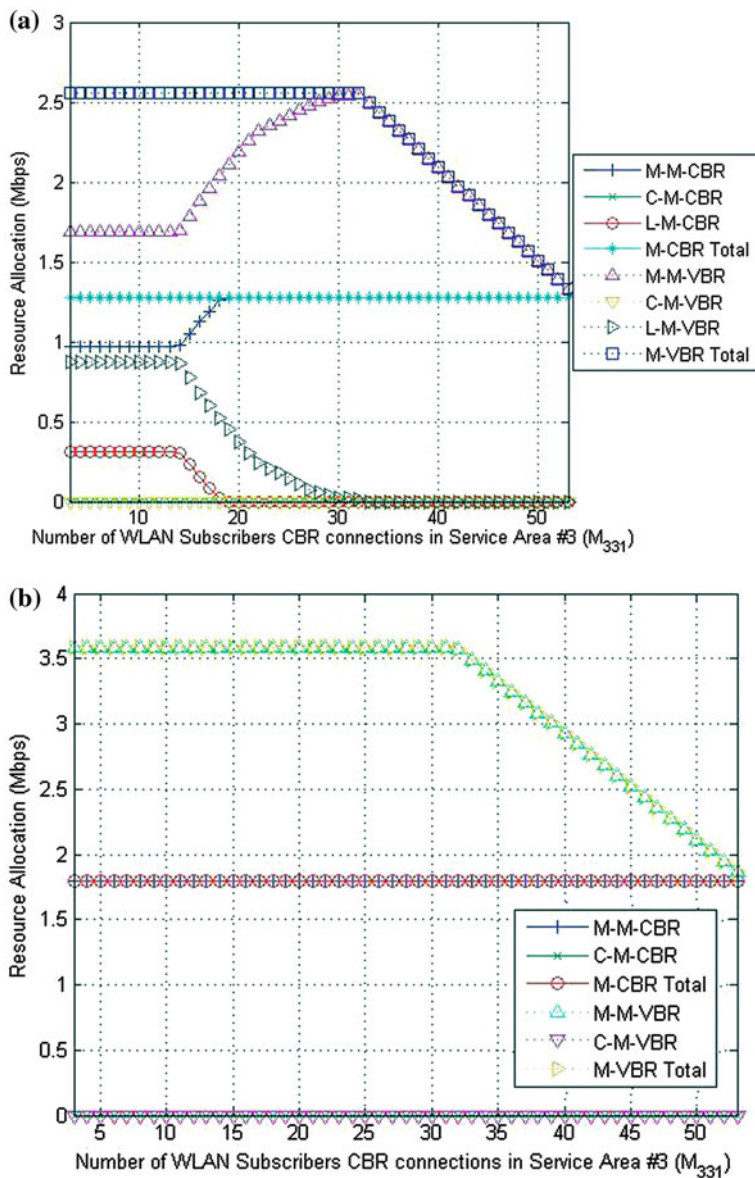


Fig. 2.8 Total bandwidth allocation by each network BS/AP to the WiMAX subscribers in **a** Area 3, **b** Area 2, and **c** Area 1

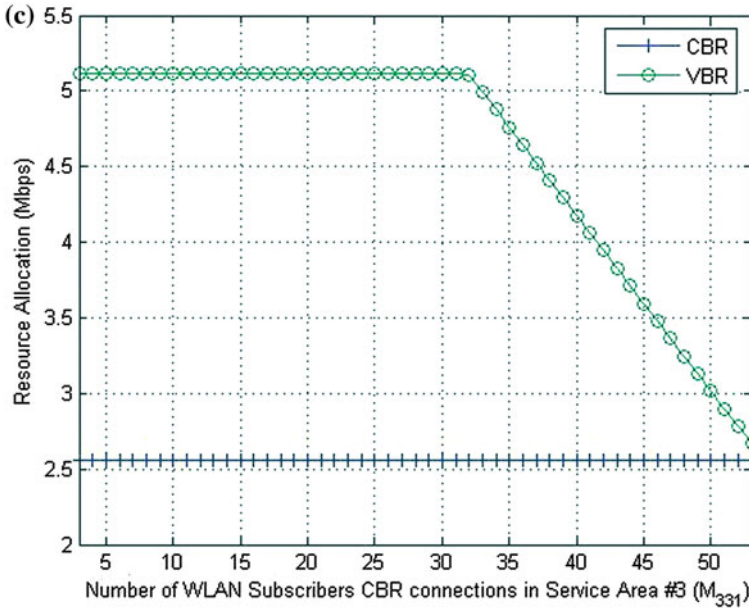


Fig. 2.8 (Continued)

bandwidth to support its own subscribers. For $M_{331} > 18$, all the required bandwidth to support the CBR calls (M-CBR-Total) in service area 3 comes from the WiMAX BS. For $M_{331} > 32$, the WiMAX BS reduces its bandwidth allocation to the VBR WiMAX subscribers towards the minimum required bandwidth to support the WLAN subscribers (refer to Fig. 2.6).

Figure 2.8b shows the total allocated bandwidth by each network BS/AP to the WiMAX subscribers in service area 2. The total allocated bandwidth comes only from the WiMAX BS (M-M-CBR and M-M-VBR) although the MTs lie in the coverage area of the cellular network. This is due to the associated high cost of the cellular network bandwidth. Again, as in Fig. 2.8a, for $M_{331} > 32$, the WiMAX BS decreases its allocated bandwidth to the VBR subscribers to support the WLAN subscribers in service area 3.

Figure 2.8c shows the total allocated bandwidth by each network BS/AP to the WiMAX subscribers in service area 1. Since the MTs are outside the coverage areas of the cellular network BS and WLAN AP, the total bandwidth allocation comes only from the WiMAX BS. For $M_{331} > 32$, the WiMAX BS allocated bandwidth to the VBR calls is reduced to support the WLAN subscribers in area 3.

From the results in Figs. 2.6, 2.7, and 2.8, service degradation of VBR calls starts from the cellular network subscribers as these users depend heavily on other networks in order to satisfy their required bandwidth. Because of the priority mechanism, these networks give higher priority in allocating their resources to their own subscribers,

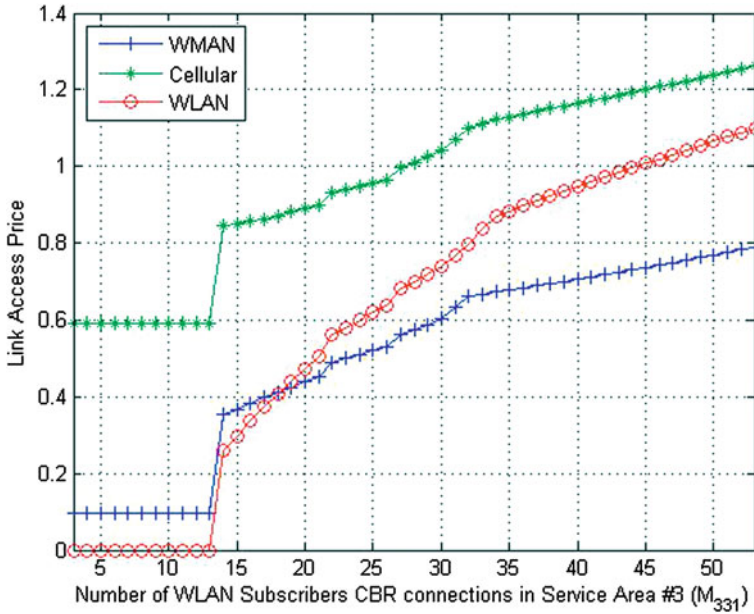


Fig. 2.9 Link access price

leading to a reduced bandwidth allocated to the VBR calls of cellular network subscribers.

Figure 2.9 shows the variation in the link access price (λ_{ns}). For $M_{331} < 14$, the WLAN AP has not yet reached its capacity limitation, resulting in its link access price value equal to zero. On the other hand, the WiMAX and the cellular network BSs have a high value of link access price as they reach their capacity limitation (refer to Fig. 2.5). The cellular network BS has the highest link access price value due to its lowest capacity. For $M_{331} \geq 14$, the BSs/AP of three networks reach their capacity limitation. This calls for a higher link access prices for all three networks. As M_{331} increases, the link access price value increases to indicate that it is more expensive to use these links. These results follow the complementary slackness condition [6]. Normally, the WLAN AP has a lower link access price than the WiMAX BS, since the number of users supported by the WLAN AP is less than those supported by the WiMAX BS in the three areas. But as the WLAN AP gives a lower cost on its resources using the priority parameter p_{3m1} , most of the users in area 3 use its bandwidth, and the WLAN subscribers in area 3 are mainly supported by the WLAN AP, which causes the link access price for the WLAN AP to increase above the link access price value of the WiMAX BS for $M_{331} > 18$.

2.5 Summary

In this chapter, a decentralized optimal resource allocation (DORA) algorithm in a heterogeneous wireless access environment is presented. The algorithm has the following features:

1. It is a decentralized algorithm. Each network BS/AP solves its own NUM problem and performs its resource allocation. No central resource manager is required.
2. It supports MTs with multi-homing capabilities for multi-services, namely, CBR and VBR services.
3. It allows for service differentiation, among the network subscribers and the other users. As a result, the network subscribers enjoy their maximum required bandwidth using their home network resources.
4. The MTs play an active role in the resource allocation operation by coordinating the available wireless access networks to satisfy their required bandwidth.

The algorithm is limited to a static system with no arrival of new calls or departure of existing ones with the objective of identifying the role of different network entities in such a decentralized architecture model. In the next chapter, we discuss the main limitations of the DORA algorithm in a dynamic system with call arrivals and departures and present some modifications to address these limitations.

Cooperative Networking in a Heterogeneous Wireless
Medium

Ismail, M.; Zhuang, W.

2013, VIII, 90 p. 29 illus., Softcover

ISBN: 978-1-4614-7078-6