Chapter 1

A Framework for Decentralized Wireless LAN Resource Management

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The proliferation of wireless local area network (WLAN) deployments in enterprises, public areas, and homes will cause frequent geographical coverage overlap among multiple networks. A recent growing interest is the coordination among WLAN providers for efficient resource management over a large coverage area. While radio resource management for a single WLAN has been studied extensively, little research work addresses cooperative resource management over multiple WLANs. The lack of cooperative resource management can cause significant performance degradation due to inter-WLAN interference. Moreover, unbalanced loads among multiple networks can incur congestion in a few WLANs while foregoing unused excess resources in others. Hence, resource management among multiple WLANs can make the best use of available radio resources and accommodate more users system-wide. In this chapter, a fully decentralized cooperative resource management framework using multi-agent systems for multiple WLANs in interference environments is explained that incorporates the predictability of network states and decentralized control through multi-agent systems. The proposed framework emphasizes the underlying predictability of network conditions and promotes management solutions tailored to different interference environments. The impacts of both inter-WLAN co-channel interference and co-located interference sources from wireless personal area networks (WPANs) are considered.

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1.1. Introduction

There has recently been a remarkable increase in the usage of IEEE 802.11-based wireless local area networks (WLANs) [1] due to low cost, installation simplicity, and high data rates. Many hot spots are emerging and multiple WLANs are being deployed within a small geographic vicinity such as office buildings, multi-tenant residential complexes, city downtown areas, and university campuses. Different WLANs in a particular area may be deployed by different operators. In such an environment with multiple WLANs co-existing, a growing interest is that WLAN providers may set up reciprocal agreements and coordinations so that mobile users may share the usage of multiple WLANs.

A direct benefit of resource sharing among multiple WLANs is the expansion of network coverage. A WLAN usually suffers limited communication range. By integrating different overlapping WLANs, WLAN providers can offer value-added inter-WLAN roaming services to subscribers who need wider roaming areas. Meanwhile, mobile users can roam among multiple networks, enjoying the wide-area wireless access. Another benefit of this integration is the cooperation of resource management among multiple WLANs. Radio resources of each network are usually managed independently. The lack of cooperative resource management can cause significant performance degradation due to *inter-WLAN interference* [2]. Moreover, unbalanced loads among multiple networks can incur congestion in a few WLANs while foregoing unused excess resources in others. Hence, resource sharing among multiple WLANs can make the best use of available radio resources and accommodate more users system-wide. At the same time, WLAN providers may also benefit from being able to improve service quality and network utilization through cooperative WLAN resource management.

WLANs and wireless personal area networks (WPANs) often operate in a shared spectrum, the 2.4GHz unlicensed industrial, scientific, and medical (ISM) band. When a WLAN such as the IEEE 802.11b is co-located with a WPAN such as Bluetooth or the IEEE 802.15.4 low-rate WPAN (LR-WPAN), the issue of coexistence between different wireless networks needs to be considered to ensure their performance requirements are maintained [3–6]. Co-location of wireless services may occur under a number of different scenarios. For example, a WPAN can be deployed to support a sensor array within the same location as an established WLAN. Alternatively, a hierarchical network structure based on the strengths of each wireless service is straightforward to envision, where WPANs support local connectivity and WLANs provide the backbone for multiple WPANs. Therefore, resource management of WLANs will operate in a dynamic RF environment often involving a diverse set of co-located wireless services.

Co-located wireless networks operating in the same unlicensed frequency band can cause interference to each other because of spectral overlap. Interference sources will impact mobile stations differently due to variations in RF path loss. Even if stations are at fixed locations, dynamics in the environment will significantly impact the RF propagation characteristics. These variations make it difficult and costly, in terms of radio resources, to maintain performance requirements. Hence, it is imperative that the dynamic effects of interference be incorporated into network management and control decision-making.

Network management can be implemented through a centralized or distributed control method, or a hybrid one. A centralized method involves a centralized controller and is able to provide the global optimal solution, but requires periodic global information gathering on network states at the centralized controller and has the weakness of scalability. On the other hand, a distributed method has the advantages of scalability and easy collection of local inputs, but may lead to local optimal solutions and longer convergence time of solution-finding. A recent research effort on distributed control is to apply the agent technology to intelligent network management and data harvesting. Agents are autonomous entities that receive sensory inputs from the environment and then act on it using their effectors based on the knowledge they have of the environment [7]. A multi-agent system (MAS) allows for the distribution of knowledge, data, and resources among individual agents and its modularity supports the development and maintenance of complex highly reliable systems [8]. Multi-agent systems are also easier to scale up as they can speed-up computation due to concurrent processing; they have less communication bandwidth requirements since processing is located nearer the source of information and facilitate real-time responsiveness as processing, sensing, and effecting can be co-located. Several distributed control algorithms based on multi-agent systems are proposed to solve centralized control problems efficiently and proved to converge to the global optimal solution [9–12]. Various multi-agent systems have been deployed on wireless sensor networks (WSNs) and other distributed networks for data processing and energy conservation in an intelligent fashion [13–15]. However, no existing work has addressed using multi-agent systems for cooperative network management for multiple WLANs and incorporated the dynamics of the interference environment into control decision-making.

Although a considerable amount of research on radio resource management in a single WLAN has been proposed [16–19], cooperative resource management for multiple WLANs remains largely unexplored. Moreover, few protocols and algorithms incorporate the prediction of dynamic RF operational statistics from interference environments and investigate the application of multi-agent systems for distributed intelligent network management. Therefore, predictability-based cooperative resource management for multiple WLANs using multi-agent systems is proposed in this chapter. Predictability-based approaches may capture the effects of the time-varying nature of network links. It also helps determine the degree to which the state of the network can be reliably observed. By using predictability-based management approaches with the help of multi-agent systems, the changing operating conditions of multiple networks and the potential interference to WLANs from diverse co-located devices can be captured in advance and this information can be distributed timely through multiple agents, which may help the decision-making of resource management.

In this chapter, we focus on how to adaptively manage shared system-wide resources under time-varying network conditions among multiple WLANs in WLAN/WPAN interference environments. The impacts of both inter-WLAN co-channel interference and co-located interference sources from WPANs are considered. A fully decentralized resource management framework that incorporates the predictability of network states and the coordination between physical environment modeling and network management using multi-agent systems is proposed.

The rest of this chapter is organized as follows. In Section 1.2, existing work on WLAN resource management is described. In Section 1.3, a centralized multi-domain WLAN resource management approach is first introduced. The goal of this centralized approach investigation is to get design insights and performance benchmark for the proposed decentralized approach. In Section 1.4, the proposed framework for decentralized WLAN resource management based on multi-agent systems is explained in detail, followed by the conclusions in Section 1.5.

1.2. Existing Work on WLAN Resource Management

Resource management for WLANs include dynamic channel assignment, dynamic transmit power control, and load balancing [16]. In this work, we focus on resource management for load balancing.

Resource management for load balancing in wireless networks has been extensively studied. In cellular networks, load balancing is usually achieved through dynamic channel allocation [20, 21]. This technique is not as suitable in WLANs where each access point (AP) normally uses one channel. Another approach is to use cell overlapping to reduce the blocking probability of calls and maximize the network utilization [22, 23]. In [24, 25], load balancing integrated with coordinated scheduling techniques for multi-cell packet data networks is proposed. However, these techniques consider different objective functions such as call blocking probability, which is not applicable for the load balancing issue in the WLAN context [18].

Approaches for load balancing in a single WLAN can be classified into two categories. One is association control through which the network redistributes client associations among APs more or less uniformly so that no one AP is unduly overloaded [16]. The other is capacity control through which the network adjusts the maximum allowable throughput of each AP so that heavy-loaded APs can have more capacity to support users [2]. Three different techniques are proposed for association control. The *explicit channel switching* algorithm requests client stations to explicitly change their association from an overloaded AP to a less loaded neighboring AP [18, 19]. This algorithm trades off received signal strength with load by forcing stations to switch from an overloaded AP with a stronger signal to a lightly loaded AP with a possibly weaker signal within the radio range of the stations. In [17], an algorithm incorporating transmit power control and channel switching is proposed. Load balancing is achieved by adjusting transmit power of neighboring APs to change their radio coverage pattern. In this way, the coverage area of the overloaded AP is reduced, causing some of its client stations to handoff to lightly loaded APs with enlarged coverage areas. The third technique is *network directed roaming* under which the network balances load by providing explicit feedback to users about where to roam to get the services they require [19]. This technique can achieve global load balancing over the entire WLAN, while the first two try to distribute load among neighboring APs.

All the above load balancing schemes are designed for a single WLAN. They cannot be directly applied to multi-domain WLANs because they cannot provide system-wide fair resource allocation among multiple networks. Co-located WLANs often use the same limited number of orthogonal channels (e.g., three orthogonal channels are available in IEEE 802.11 b/g networks). Hence, the effect of inter-domain co-channel interference becomes severe as the number of co-located WLANs increases. The load of a cell in one domain determines the level of its interference on other co-channel cells both inside and outside the domain. Therefore, achieving system-wide fair resource allocation should not be restricted to only independent load balancing per domain without global cooperation. It should incorporate the load and interference interactions between different domains. In [2], an inter-domain radio resource management scheme for WLANs is proposed. This work provides an exciting insight into the optimization of resource sharing among multiple domains. However, the interactive effects of co-channel interference among multiple domains are not considered in the optimization process.

To the best of our knowledge, very little research work addresses cooperative resource management over multiple WLANs. Moreover, very little work on resource management for either single or multiple WLANs has considered the interference from possible co-located WPANs in the operational environment. As stated previously, WPAN interference sources require the WLAN to consume additional network resources in order to maintain performance requirements. Therefore, it is imperative that the dynamic effects of co-located WPAN interference be incorporated into network management.

1.3. Third-Party-Based Centralized WLAN Resource Management

Multi-domain WLAN resource sharing and management can be implemented through either a centralized approach or a decentralized approach. Under the centralized approach, a centralized controller collects estimates of resource utilization and interference level from all APs in multiple WLANs and generates global optimal control decisions to feed back to each AP. The resource optimization under the centralized architecture can achieve the global optimal performance, which can be used as a performance benchmark for the decentralized approach.

Therefore, we first conduct research on using a centralized resource optimization approach for multi-domain WLANs. Then, the performance results from this centralized approach will be used as a benchmark for our proposed decentralized approach to achieve the global optimal performance.

1.3.1. *Third-Party-Based Centralized Architecture*

We first propose a third-party-based centralized resource management architecture for the integration of multiple WLANs. A new entity, *local network controller (LNC)*, is connected to all the APs of multiple WLANs, as shown in Fig. 1.1. WLANs under the control of an LNC form a *WLAN cluster*. The LNC acts as a radio resource coordinator across domains and takes care of issues related to inter-domain roaming and resource sharing within a WLAN cluster. The LNC can integrate any number of WLANs belonging to different providers. As the number of domains in a WLAN cluster increases, the LNC can be built in a hierarchical structure to make it more scalable. As shown in Fig. 1.1, a *global network controller (GNC)* is connected to all LNCs supporting inter-WLAN-cluster roaming and resource sharing. When a mobile station (MS) roams between WLANs in different WLAN clusters or when load balancing over multiple WLAN clusters needs to be addressed, the GNC is involved for resource management. A third-party agent can be the operator of the LNCs and GNC. It is responsible for the design, implementation, and maintenance of the control functions provided by the LNCs and GNC.

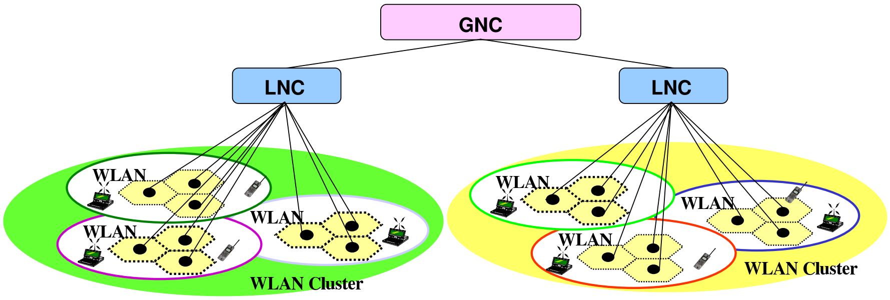

Fig. 1.1. Third-party-based multi-domain WLAN resource management architecture.

Providers of different WLANs in a WLAN cluster set up service level agreements with the LNC. The operator of the LNC generates revenue from WLAN providers who agree to share their network resources with others. A similar business model is used by iPass [26] to provide global remote access services. Through the coordination of the LNC, providers may offer inter-WLAN roaming services to their subscribers as a value-added service feature. They can also support communications with better-quality signals since the impact of interactive interference is globally balanced across the

WLAN cluster through the control of the LNC. The functions related to user authentication, billing, security and privacy, and mobility management can be implemented in the LNC using similar models proposed in [27]. Here, we focus on how to fairly balance system-wide resources in order to accommodate more users with the least amount of cost.

The LNC gathers the measured resource usage statistics from all the APs via Simple Network Management Protocol (SNMP) [28]. SNMP also provides security related functions such as user authentication and message encryption [29]. Most enterprise-class APs can support SNMP [2]. APs collect signal characteristics from client stations in each domain. The IEEE 802.11k task group [30] is developing a radio resource measurement extension to the IEEE 802.11 WLAN standard. As suggested by the IEEE 802.11k task group, a portion of the signal characteristics are obtained directly from the WLAN cluster. The data can be augmented by an additional sensing network, potentially located at each AP, to provide additional data specifically associated with WPAN interference sources in the environment. The measured data can then be used by the LNC to generate the control decisions to optimize the performance of the entire WLAN cluster.

The LNC and APs periodically collect the required information for resource management. The LNC calculates the optimal resource allocation across domains and applies control decisions to APs. The decision-making is updated periodically in order to address changes in the traffic load and interference environment. Note that the load at APs does not vary frequently, if stations are not highly mobile. Previous studies on WLAN measurement and user behavior show that users have a quasi-static mobility pattern [31–33], which means, users are free to move from place to place, but they tend to stay in the same physical locations for long time periods [18]. In addition, it is important to remark that the periodic data-collecting from stations does not imply measuring instantaneous small-scale multipath signal characteristics which are very time-sensive. Instead, measurements should be targeted at capturing large-scale changes in signal characteristics due to variations in traffic pattern, station mobility, interference sources, and interference mobility. In other words, the measurement is based on the factors which influence the LNC management of the WLAN performance. Therefore, control decisions need not be updated frequently and they should target long-term performance improvement. Thus, the control overhead resulting from the periodic updating can be kept at a reasonable level.

1.3.2. *Resource Utilization Modeling and Optimization*

In this section, we introduce the resource management scheme for multi-domain WLANs under the third-party-based centralized architecture.

1.3.2.1. *Motivation*

We first use the example shown in Fig. 1.2 to explain the interactions between different WLAN domains due to cell load and co-channel interference.

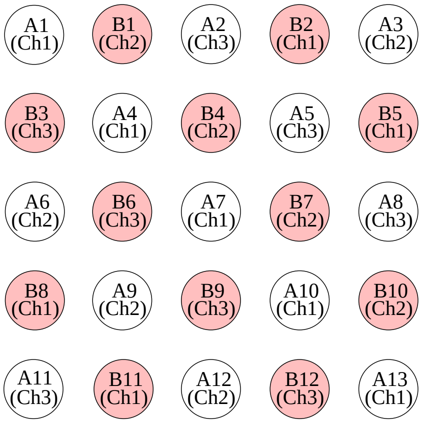

Fig. 1.2. Cell layout of two co-located WLANs A and B.

In Fig. 1.2, two IEEE 802.11b WLANs, A and B, are co-located in the considered region. Each circle represents an AP: 13 APs for WLAN A and 12 APs for WLAN B. The locations of APs and the channels used by APs are shown in the figure. Since only three non-overlapping channels are available, the channels are selected so that the APs using the same channel are geographically separated the furthest.

When multiple WLANs co-locate, the traffic load carried by one WLAN will impact the resource utilization of other WLANs due to co-channel interference. This is illustrated in Fig. 1.2 by considering cell 4 in WLAN A which operates on frequency channel 1. If offered traffic load is increased in this cell, then the impact will be felt in closeby cells sharing the same frequency channel, i.e., cells 1 and 7 in WLAN A and cells 2 and 8 in WLAN B. Depending on the RF propagation characteristics, it is possible for additional cells to be impacted by interference signals which are of sufficient strength to cause contention within nearby cells. Therefore, stations in the impacted area contend for the channel based on the additional interference traffic. From the figure, it can be observed that optimizing the load in domain A independent of the resource requirement of domain B is likely to impact domain B's performance. As a result, load balancing techniques designed for one domain may not be suitable for multiple co-located WLANs if the inter-relationship between co-located domains is not taken into consideration. This is the motivation for developing a new resource management scheme in a multi-domain environment.

1.3.2.2. *Overview of the Resource Management Scheme*

The goal of the resource management scheme is to minimize the total system cost by adjusting resource allocation in each domain. The cost is what the system needs to pay to support all the client stations to achieve performance requirements. It is related to the available radio resources for supporting the offered load in each domain and mitigating interference from the operational environment. The LNC manages resource sharing across domains by controlling the maximum allowable throughput of each AP. When the maximum allowable throughput at an AP changes, the available radio resources of the cell is limited. Consequently, the cell utilization changes which leads to a different system cost. Therefore, minimizing the overall system cost is equivalent to finding the optimal allowable throughput at each AP. In addition, WPAN interference can adversely affects the WLAN performance by changing its resource utilization requirements and thereby needs to be considered. Moreover, due to the dynamics in the RF environment, signal characteristics, traffic load, and interference intensity are time-variant. As a result, the optimal resource allocation decision should be dynamically adjusted to reflect the influences of the time-varying environment.

The resource management scheme under the third-party-based centralized architecture includes three steps. First, based on the overall traffic load distribution at all the APs in a WLAN cluster, the impact of co-channel interference at each cell can be calculated. Then, by incorporating the impact of interference from other sources in the operational environment, the communication cost of the overall system can be derived which is a function of cell load, co-channel interference, and interference from other wireless services. Second, the LNC finds the optimal pattern of maximum allowable throughput at each AP in multiple domains. In other words, the LNC decides which AP should provide how much capacity to its users. This optimal throughput pattern results in the minimum system cost. Finally, the LNC sends control signals to APs to instruct them on how to update their allowable resources for users based on the calculated optimal throughput. Therefore, by the global control of the LNC on restricting the maximum allowable throughput at APs, the effect of co-channel interference is balanced across multiple domains and thereby the overall system resource utilization is minimized. Note that it is up to the individual WLANs to determine which method should be used to achieve the optimal throughput, e.g., load balancing within the domain, limiting average throughput, etc.

1.3.3. *Problem Formulation*

There are four possible resource management scenarios in multi-domain WLANs as follows:

(1) *Intra-domain* resource optimization *without* the consideration of potential interference from co-located WPANs,
(2) *Intra-domain* resource optimization *with* the consideration of potential interference from co-located WPANs,
(3) *Inter-domain* resource optimization *without* the consideration of potential interference from co-located WPANs,
(4) *Inter-domain* resource optimization *with* the consideration of potential interference from co-located WPANs.

Scenarios 1 and 2 are the cases that each domain optimize radio resource usage independently. The already proposed load balancing techniques designed for a single WLAN can be applied to scenario 1. Scenarios 3 and 4 involve the LNC to help control the resource allocation in each domain.

The intra- and inter-domain load balancing issue can be formulated as an optimization problem. The LNC controls the maximum allowable throughput of each AP. It periodically optimizes the resource usage in each domain by minimizing the overall system cost function $F(\cdot)$ where $F(\cdot)$ is the total communication cost the system needs to pay for supporting all the client stations. More specifically, assume there are M domains in a WLAN cluster. Let $\mathbf{N^T} = [N_1, N_2, \cdots, N_M]$ be the number of APs in each domain. Hence, for a particular domain j, there are N_j APs in the network. Let $\mathbf{C_j^T} = [C_{1j}, C_{2j}, \cdots, C_{N_j j}]$ be the maximum allowable throughput of each AP in domain j. The objective function and the constraints for intra-domain resource optimization in domain j are:

$$\begin{aligned} \text{Minimize} \quad & F_{intra}(\mathbf{C_j}) = \sum_{i=1}^{N_j} \Phi\left(f_{ij}(C_{ij}, I_{co\_ij}, I_{e\_ij})\right) \\ \text{Subject to} \quad & f_{ij}(\cdot) \le 1 \\ & \mathbf{e^T C_j} \le T_{D_j} \\ & C_{min} \le C_{ij} \le C_{max} \end{aligned} \tag{1.1}$$

where $f_{ij}(C_{ij}, I_{co\_ij}, I_{e\_ij})$ is the normalized resource usage at cell i in domain j, I_{co_ij} is the co-channel interference from other cells in the domain to cell i, and I_{e_ij} is the interference from other co-located WPANs to cell i. The resource usage at a cell is determined by the cell utilization U, co-channel utilization I_{co}, and environmental interference I_e. The cell utilization U can be approximated by calculating the ratio of the measured load to the maximum allowable throughput [2], i.e., $U_{ij}\left(I_{e\_ij}\right) = \frac{\rho_{ij}(I_{e\_ij})}{C_{ij}}$, where ρ_{ij} is the time-varying measured load at cell i in domain j. Thus, $f_{ij}(C_{ij}, I_{co\_ij}, I_{e\_ij})$ is:

$$\begin{aligned} f_{ij}(C_{ij}, I_{co\_ij}, I_{e\_ij}) &= U_{ij}\left(I_{e\_ij}\right) + I_{co\_ij}\left(I_{e\_ij}\right) \\ &= \frac{\rho_{ij}\left(I_{e\_ij}\right)}{C_{ij}} + I_{co\_ij}\left(I_{e\_ij}\right) \end{aligned} \tag{1.2}$$

where $U_{ij}(\cdot)$, $\rho_{ij}(\cdot)$, and $I_{co\_ij}(\cdot)$ are functions of the WPAN interference as presented in Section 1.3.3.2. $\Phi(\cdot)$ is a mapping function to map the resource usage to cost. It should be chosen as a convex function to get an effective strategy to facilitate optimization [34]. $\mathbf{e^T}$ is a unit vector with adequate dimension and $\mathbf{T_D^T} = [T_{D_1}, T_{D_2}, \cdots, T_{D_M}]$ is the maximum capacity of each domain. If no inter-domain resource cooperation, the maximum domain throughput is the maximum data rate that can be supported by WLAN products. C_{min} and C_{max} are the minimum and maximum allowable throughput in each cell, respectively. (1.1) shows that for intra-domain resource optimization, the LNC finds the maximum allowable throughput for each AP in the domain which results in the minimum communication cost.

For inter-domain resource optimization, the LNC not only finds the optimal throughput pattern for all the APs, but also determines the optimal capacity for each domain. In other words, the LNC optimizes the global resource sharing among multiple domains by finding the optimal $\mathbf{T_D^T} = [T_{D_1}, T_{D_2}, \cdots, T_{D_M}]$ which leads to the minimum overall system cost. The objective function and the constraints for inter-domain resource optimization in domain j are:

$$\begin{aligned}
\text{Minimizing} \quad & F_{inter}(\mathbf{C_j}) = \sum_{i=1}^{N_j} \Phi\left(\tilde{f}_{ij}(C_{ij}, \tilde{I}_{co\_ij}, I_{e\_ij})\right) \\
\text{Subject to} \quad & \tilde{f}_{ij}(\cdot) \leq 1 \\
& \mathbf{e^T C_j} \leq T_{D_j} \\
& C_{min} \leq C_{ij} \leq C_{max} \qquad (1.3)
\end{aligned}$$

Here, $\tilde{f}_{ij}$ is different from that in (1.1) since $\tilde{I}_{co\_ij}$ includes interference from co-channel cells both inside and outside domain j. The optimal allowable throughput $\mathbf{C_j^*}$ is given by

$$\mathbf{C_j^*} = \arg\min_{\mathbf{C_j}} F_{intra}(\mathbf{C_j}) \qquad (1.4)$$

or

$$\mathbf{C_j^*} = \arg\min_{\mathbf{C_j}} F_{inter}(\mathbf{C_j}). \qquad (1.5)$$

After the LNC finds the optimal resource allocation, resources at each domain should be updated. Therefore, at each time step, T_{D_j} is updated to optimize the global resource sharing. Assume $T_{D_j}^{(m)}$ is the maximum capacity of domain j after time step m. Then at time step $m+1$, T_{D_j} should be updated based on

$$T_{D_j}^{(m+1)} = T_{D_j}^{(m)} + \alpha\left(\psi_{D_j} - \widehat{E}[\Psi_D]\right) \qquad (1.6)$$

where α is a constant controlling the update rate, ψ_{D_j} is the cross-domain impairment for domain j which is obtained by

$$\psi_{D_j} = F_{inter}(\mathbf{C_j}) - F_{intra}(\mathbf{C_j}) \qquad (1.7)$$

and $\widehat{E}[\Psi_D]$ is the sample mean over $\Psi_D = \left[\psi_{D_1}, \cdots, \psi_{D_j}, \cdots, \psi_{D_M}\right]$. Hence, $\widehat{E}[\Psi_D] = \frac{1}{M}\sum_{j=1}^{M} \psi_{D_j}$. The LNC periodically finds the optimal resource allocation and instructs APs updated resources based on (1.6).

1.3.3.1. *Interference from Co-located WLANs*

The method used for deriving $\tilde{I}_{co\_ij}$ is the same as presented in [2], which is

$$\tilde{I}_{co\_ij} = \sum_{d=1}^{M} \sum_{\substack{\ell=1 \\ \ell \neq i}}^{N_d} \left[\delta_{\ell d|ij} \cdot U_{\ell d} \cdot S_{\ell d|ij}/S_{ij}\right] \qquad (1.8)$$

where

$$\delta_{\ell d|ij} = \begin{cases} 1 \text{ AP frequency channels are the same for} \\ \quad \text{cell } \ell \text{ in domain } d \text{ and cell } i \text{ in domain } j \\ 0 \text{ otherwise} \end{cases} \tag{1.9}$$

N_d is the number of APs in the dth domain, S_{ij} is the coverage area for cell i in domain j, and $S_{\ell d|ij}$ is the overlap region between cell i in domain j coverage area and the interference area of cell ℓ in domain d. Every AP is assigned a single frequency channel and MSs are assumed to be uniformly distributed within the AP's coverage area. MSs are associated with their nearest AP. The coverage area and interference area are approximated by circles. As in [2], the ITU-R P.1238-2 indoor path loss model was used in evaluating $S_{\ell d|ij}$ which is expressed as

$$P_L = 20\log_{10} f + 10n\log_{10} d - 28 \text{ (dB)} \tag{1.10}$$

where P_L is the RF signal propagation path loss based on distance d between the AP and the MS, f is the carrier frequency in MHz, and n is the path loss exponent.

In a similar fashion to (1.9), I_{co_ij} is defined based on the co-channel interference within domain j only:

$$I_{co\_ij} = \sum_{\substack{\ell=1 \\ \ell \neq i}}^{N_d} \left[\delta_{\ell j|ij} \cdot U_{\ell j} \cdot S_{\ell j|ij}/S_{ij}\right]. \tag{1.11}$$

1.3.3.2. *Interference from Co-located WPANs*

Next, we explain how to obtain the interference from co-located WPANs, I_e. Fig. 1.3 illustrates a general scenario in which cell i in domain j (located at x_{AP_ij}) and an associated MS (located at x_{STA_ij}) are co-located with the kth WPAN (located at x_{BT_k}). We use Bluetooth technology as an example of WPANs to derive I_e here. Due to the WPAN interference, packet retransmissions can be required in order to successfully transmit a packet between the AP and MS. The packet retransmission, in essence, increases the traffic load within the cell and thereby increases the utilization of the cell, i.e.,

$$U_{ij}\left(I_{e\_ij}\right) = \frac{\rho_{ij}\left(I_{e\_ij}\right)}{C_{ij}} = \frac{\rho_{ij}\overline{N}_{Tx}(i,j)}{C_{ij}} \tag{1.12}$$

where $\overline{N}_{Tx}(i,j)$ is the expected number of transmissions required to successfully transmit a packet within cell i in domain j based on the local

WPAN interference environment. The expected number of transmissions can be evaluated by

$$\overline{N}_{Tx}(i,j) = 1 + \frac{\Pr[C|i,j]}{1-\Pr[C|i,j]} = \frac{1}{(1-\Pr[C|i,j])} \tag{1.13}$$

where $\Pr[C|i,j]$ is the probability of requiring a packet retransmission due to interference from one or more WPAN interference sources, i.e., the probability of collision is given by

$$\Pr[C|i,j] = \sum_{k=1}^{W} \Pr[C_k|i,j] - \sum_{l=1}^{W} \sum_{\substack{k=1 \\ k\neq l}}^{W} \Pr[C_k|i,j] \cdot \Pr[C_l|i,j] + \cdots \tag{1.14}$$

where W is the number of co-located WPAN interferers. (1.14) assumes the collision probabilities, $\Pr[C_k|i,j]$, for each of the active interference sources are independent. $\Pr[C_k|i,j]$ takes into account the dynamics between the interference signal's characteristics and the desired signal's characteristics at the intended receiver.

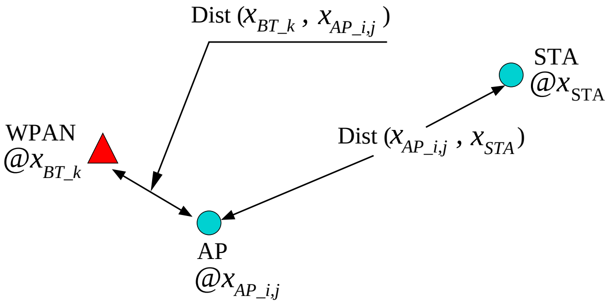

Fig. 1.3. Cell layout with co-located WPAN interferers.

In order to evaluate $\overline{N}_{Tx}(i,j)$ based on (1.13), the collision probability $\Pr[C_k|i,j]$ needs to model the specific interference scenario. For the scenario where WPANs based on Bluetooth technology are operated in an IEEE 802.11b WLAN environment, the collision probability is associated with the likelihood that a Bluetooth packet and an IEEE 802.11b packet are time and frequency coincident and the interference signals have sufficient power to cause an error. In evaluating $\Pr[C_k|i,j]$, the likelihood that the interference and desired signals are both time and frequency coincidence needs to be determined such that the interference signal has sufficient power to cause an error in the desired packet's reception. Based on the relative timing between the IEEE 802.11b packet transmission with the Bluetooth packet frame timing, the number of Bluetooth packets time coincident with the 802.11b packet transmission is either n_r or $n_r - 1$ with corresponding probabilities $\Pr[n_r]$ and $\Pr[n_r - 1]$. Based on typical packet lengths for each of the wireless standards, n_r is either 1 or 2 [3]. These two events are independent. Therefore,

$$\Pr[C_k|i,j] = \Pr[n_r] \Pr[C_k|i,j,n_r] + \Pr[n_r - 1] \Pr[C_k|i,j,n_r - 1] \quad (1.15)$$

where $\Pr[C_k|i,j,n_r]$ is the probability of collision given the IEEE 802.11b packet overlaps in time with n_r Bluetooth packets. Since Bluetooth transmissions are based on frequency hopping, the likelihood of frequency coincidence for each of the n_r packets is independent. Therefore,

$$\Pr[C_k|i,j,n_r] = 1 - \left(1 - L_{BT} \Pr\left[C_f|i,j,\Omega_{I/S}(i,j,x_{BT\_k})\right]\right)^{n_r} \quad (1.16)$$

where the parameter L_{BT} models the loading factor for a given Bluetooth piconet, i.e., the percentage of time slots utilized by both the master and the slaves. $\Pr[C_f|i,j,\Omega_{I/S}(i,j,x_{BT\_k})]$ is the probability the interfering signal is frequency coincident with sufficient power to cause interference within cell i in domain j. The term $\Omega_{I/S}(i,j,x_{BT\_k})$ represents the interference-to-signal-power ratio (I/S) in dB at the receiver. For this study, the I/S is characterized for each cell by evaluating the received signal power at the AP from a typical MS located within its coverage area. The I/S ratio expressed in dB is given by

$$\Omega_{I/S}(i,j,x_{BT\_k}) = \Omega_{BT\_k} - \Omega_{AP} - 10n \log_{10}\left(\frac{\mathrm{Dist}_E(x_{AP}, x_{BT\_k})}{\overline{\mathrm{Dist}_E}(x_{AP}, x_{STA})}\right) \quad (1.17)$$

where Ω_{AP} and Ω_{BT_k} are typical IEEE 802.11b and Bluetooth transmit powers, respectively, expressed in dBm, n is the path loss exponent, $\mathrm{Dist}_E(x,y)$ is the Euclidean distance between x and y, and $\overline{\mathrm{Dist}_E}(x_{AP}, x_{STA})$ is the expected distance between the AP and an MS within its coverage area. Based on the Bluetooth hopping sequence uniformly covering the ISM band with bandwidth B_{UL}, $\Pr\left[C_f|i,j,\Omega_{I/S}(i,j,x_{BT\_k})\right]$ is expressed as:

$$\Pr\left[C_f|i,j,\Omega_{I/S}(i,j,x_{BT\_k})\right] = \frac{2}{B_{UL}} \int_0^{B_{UL}/2} \Pr\left[\Omega_{I/S}(i,j,x_{BT\_k}) \geq \gamma(f_{offset})|f_{offset}\right] df_{offset} \quad (1.18)$$

where $\gamma(f_{offset})$ is a random variable representing the susceptibility of the 802.11b receiver to Bluetooth interference based on the frequency offset, f_{offset}, between the two signals' carrier frequencies. $\gamma(f_{offset})$ is modeled as a Gaussian random variable based on analysis with empirical data.

1.3.3.3. *Summary*

The procedure of the multi-domain WLAN resource management scheme under the third-party-based centralized architecture is summarized in Fig. 1.4.

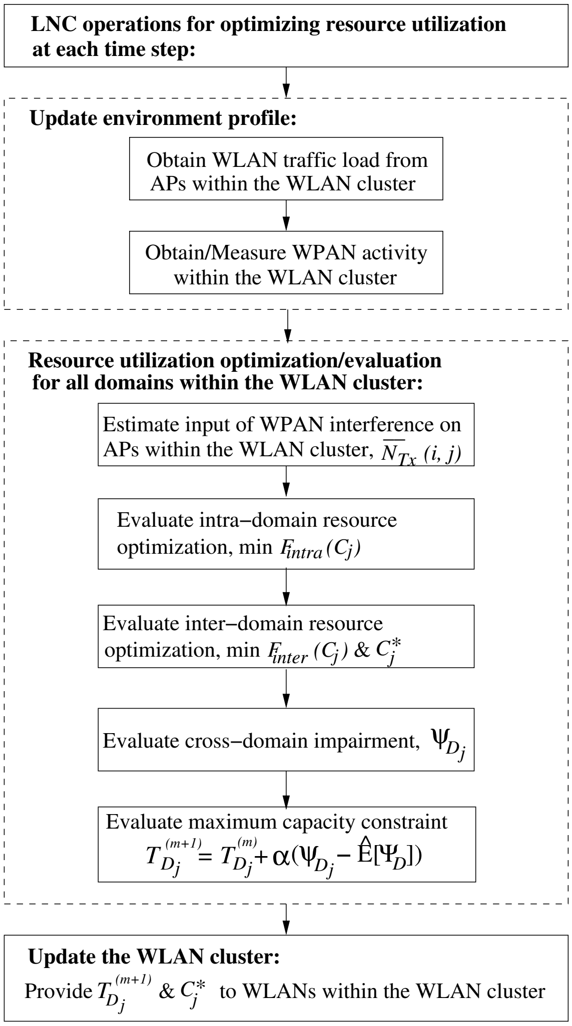

Fig. 1.4. Procedure of the inter-domain WLAN resource management scheme.

1.3.4. *Performance Evaluation*

In this section, we conduct simulation to demonstrate the performance improvement of the inter-domain resource management scheme, compared with the intra-domain schemes and the inter-domain scheme but without the consideration of interference from co-located WPANs.

1.3.4.1. *Simulation Environment*

We simulate a two-domain WLAN environment with WLAN A and B co-located. Both WLANs are IEEE 802.11b-compliant networks. The locations of APs and the channels used by APs are the same as shown in Fig. 1.2. Multiple Bluetooth nodes are also co-located with the two WLANs. Their communications interfere with each other.

We define the X and Y axes as shown in Fig. 1.5. AP1 of WLAN A is located at the origin (0, 0). Each AP is separated by 30 meters. APs of domain A and domain B are placed alternately: 13 APs of domain A and 12 APs of domain B. Their channels are selected so that APs using the same frequency channel are separated geographically the furthest. The coverage area of each AP is approximated as a circle with radius 30 meters. Two Bluetooth nodes are located 10 meters away in the X direction and 20 meters away in the Y direction to each AP of domain A, respectively. An example of the simulated WLAN and WPAN co-existence environment is an office building with two WLANs deployed. Each office room may have a Bluetooth device, e.g., a Bluetooth-enabled palm pilot, a laptop with Bluetooth interface, or a Bluetooth headset, causing interference to WLAN communications.

The simulation parameters for WLANs and the Bluetooth are listed in Table 1.1. Using the WLAN outlined in Table 1.1 with (1.10), the WLAN co-channel interference radius is $\sim 82m$. This is the radius within which one AP will impact another AP's performance given they are co-channel. The impact of Bluetooth interference is based on evaluating (1.13), using (1.14) through (1.18) and evaluating the $\Pr\left[C_k|\cdot\right]$ versus I/S. In evaluating I/S, $\overline{\mathrm{Dist}}_E(x_{AP}, x_{STA}) = (\text{cell radius})/\sqrt{2}$.

1.3.4.2. *Traffic Load Characterization*

For 802.11b-compliant systems, the maximum data rate at each cell is 11Mbps. However, due to the PHY and MAC layer overhead, the net throughput is approximately 6Mbps [35]. Based on the study on a campus

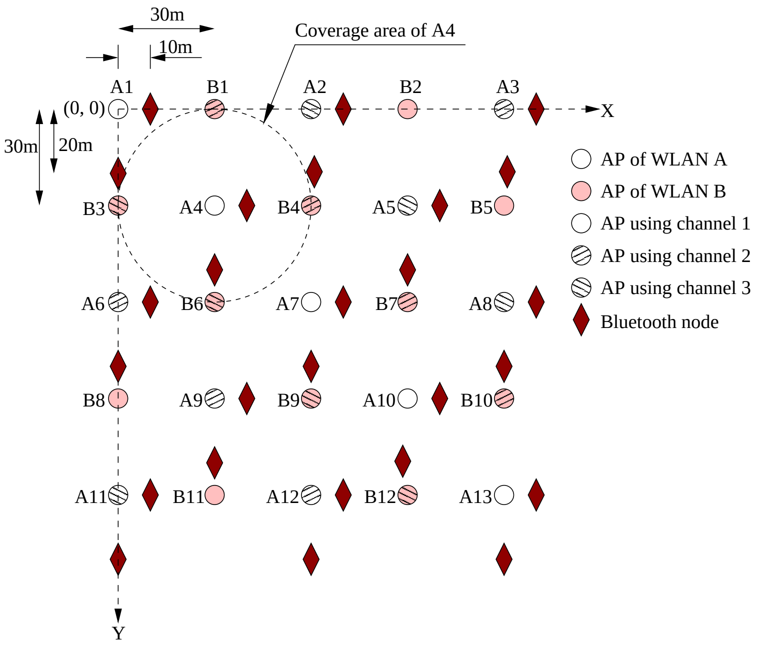

Fig. 1.5. Simulation environment with co-located 802.11b and Bluetooth.

Table 1.1. Simulation parameters.

IEEE 802.11b WLAN		
	Domain A	Domain B
Number of APs	13	12
Radio Frequency	2.4GHz	
Number of Channels	3	
Transmit Power	15 dBm	
Cell Radius	30 m	
Carrier Sense Threshold	-82 dBm	
Bluetooth		
Radio Frequency	2.4GHz	
Transmit Power	10 dBm	
Other Parameters		
Path Loss Exponent	3	
Measurement Interval	5 min	

WLAN shown in [2], the traffic load at an AP possesses characteristics of the truncated Pareto distribution with cutoff values equal to the upper limit of the MAC layer throughput, i.e., 6Mbps for IEEE 802.11b WLAN. The cumulative distribution function (cdf) of a generalized Pareto distribution is:

$$P(x) = 1 - \left(\frac{\alpha}{x}\right)^{\beta} \tag{1.19}$$

where α and β are the location and scale parameters, respectively [36]. In addition, the traffic burst duration at an AP also follows a Pareto distribution. Therefore, we use the two-state Markov traffic model shown in Fig. 1.6 for our simulation. There are two Pareto distributions involved in the model: one for the traffic load with a cutoff value at 6Mbps and the other for the HIGH/LOW state duration. The traffic is generated at both states with a burst threshold 100kbps, which means, when the generated traffic load is less than 100kbps, we assume the AP is at the LOW state. The parameters used for generating the two Pareto distributions are listed in Table 1.2.

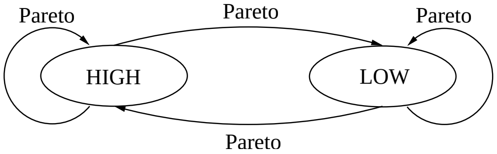

Fig. 1.6. Traffic model for simulation.

Table 1.2. Traffic parameters.

IEEE 802.11b WLAN		
	Domain A	Domain B
HIGH-State Load α	0.0096Mbps	0.0054Mbps
HIGH-State Load β	0.61	0.75
HIGH-State Load Cutoff	6Mbps	
HIGH-State Duration α	2.1 min	
HIGH-State Duration β	0.89	
LOW-State Duration α	5.3 min	
LOW-State Duration β	0.51	
Bluetooth		
Probability of Node Active	0.6	

The Bluetooth traffic model is also based on a Markov model. Activity is checked on a five-minute interval and the traffic switches from an ON to an OFF state with probability given in Table 1.2. While in the ON state, the traffic load within the Bluetooth piconet corresponds to the $\Pr[C_k|\cdot]$. Details of the traffic load model can be found in [3].

1.3.4.3. *Simulation Results*

In the following, we demonstrate the performance of the four different resource management schemes, i.e., *intra-domain* resource optimization *without* the consideration of interference from co-located WPANs (in short, intra|(no WPAN)), *intra-domain* resource optimization *with* the consideration of interference from co-located WPANs (in short, intra|WPAN), *inter-domain* resource optimization *without* the consideration of interference from co-located WPANs (in short, inter|(no WPAN)), and our proposed *inter-domain* resource optimization *with* the consideration of interference from co-located WPANs (in short, inter|WPAN).

Intra-Domain Optimization without I_e:

Fig. 1.7 shows the total system cost of the intra|(no WPAN) scheme. The solid line represents the sum of $F_{intra}(\cdot|(\text{No WPAN}))$ for each domain, where $F_{intra}(\cdot|(\text{No WPAN}))$ is obtained through (1.1) with I_e equal to 0, i.e., $N_{Tx}(i,j) = 1, \forall i, j$. Since this scheme does not consider the impact of inter-domain co-channel interference and interference from co-located WPANs, we re-evaluate the results by evaluating the optimal throughput $\left(\mathbf{C}_\mathbf{j}^*\right)_{\text{intra}|(\text{no WPAN})}$ using the inter-domain cost function with WPAN interference, i.e.,

$$\left(\mathbf{C}_\mathbf{j}^*\right)_{\text{intra}|(\text{no WPAN})} = \arg\min_{\mathbf{C}_\mathbf{j}} F_{intra}\left(\mathbf{C}_\mathbf{j}|I_e = 0\right) \tag{1.20}$$

and results re-evaluated with

$$F_{inter}\Big(\left(\mathbf{C}_\mathbf{j}^*\right)_{\text{intra}|(\text{no WPAN})}|I_e \text{based on WPAN interference}\Big) \tag{1.21}$$

The new cost is illustrated by the dashed line in the figure. It is shown in the figure that the new cost is alway higher or equal to the optimal system cost supported by the intra|(no WPAN) scheme. The gap between the two lines indicates the extra cost the intra|(no WPAN) scheme should pay for interference mitigation in order to achieve the performance requirements expected by the scheme.

Intra-Domain Optimization with I_e:

Fig. 1.8 presents the total system cost of the intra|WPAN scheme. The solid line represents the sum of $F_{intra}(\cdot|WPAN)$ for each domain, where $F_{intra}(\cdot|(\text{No WPAN}))$ is obtained through (1.1). Similar to the above case, we incorporate the impact of inter-domain interference into the optimal cost provided by the intra|WPAN scheme and show through the dashed line the

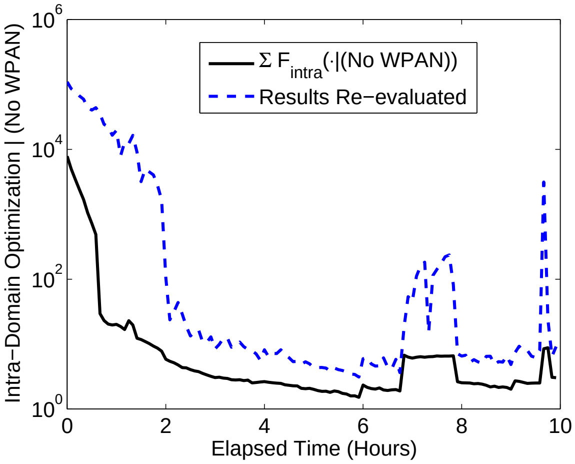

Fig. 1.7. Comparison of total cost for intra-domain optimization without consideration of WPAN interference.

actual cost the system should pay in order to achieve the expected performance. Fig. 1.7 and 1.8 tell us that independent resource optimization inside each domain cannot handle inter-domain interactions. If the system does not spend extra resources to reduce the effect from inter-domain interference, the communication quality will be lowered and the overall system resource utilization is not minimized for the offered traffic.

Inter-Domain Optimization without I_e:

Next, we present the performance of resource management when taking into account the co-channel interference from other co-located WLANs. Fig. 1.9 plots the total system cost of the inter|(no WPAN) scheme in the solid line and the re-evaluated data by incorporating the impact of interference from co-located WPANs in the dashed line. It is observed from the figure that the gap between the two lines is smaller than those in Fig. 1.7 and 1.8. The optimization control decisions made by the inter|(no WPAN) scheme are based on not only the cell utilization caused by the stations communicating in the co-channel cells inside each domain, but also the interference caused by the stations communicating in other co-located WLANs using the same frequency channel. Therefore, comparing with the intra|(no WPAN) and intra|WPAN schemes, the inter|(no WPAN) scheme results in lower system cost to maintain the same performance quality.

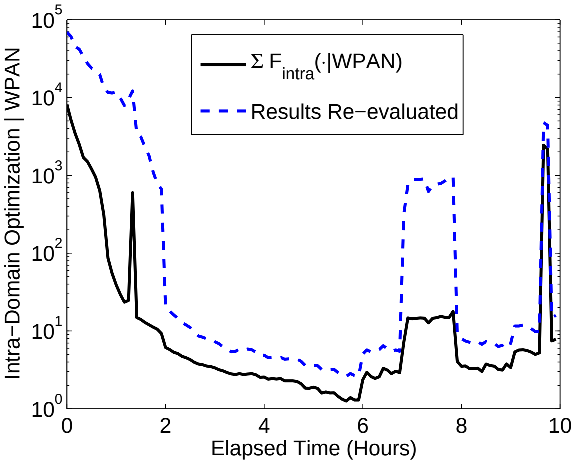

Fig. 1.8. Comparison of total cost for intra-domain optimization with consideration of WPAN interference.

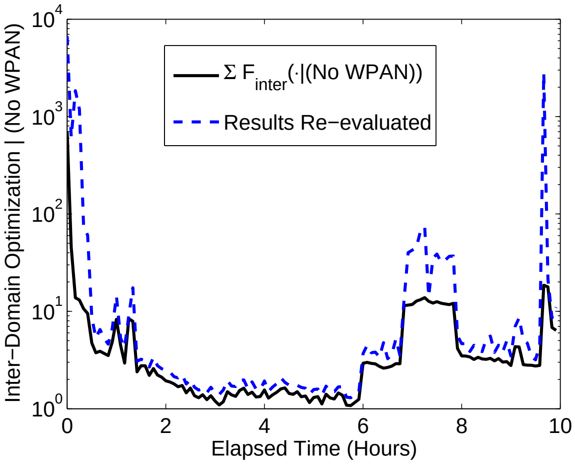

Fig. 1.9. Comparison of total cost for inter-domain optimization without consideration of WPAN interference.

Inter-Domain Optimization with I_e:

Finally, we demonstrate the performance of our proposed inter-domain resource management with the consideration of environmental interference, i.e., the inter|WPAN scheme. Fig. 1.10 plots the performance comparison of three schemes. The solid line is the cost difference of the intra|(no WPAN) scheme to the proposed inter|WPAN scheme, i.e., $\sum F_{intra}(\cdot|(\text{No WPAN})) - \sum F_{inter}(\cdot|\text{WPAN})$, while the dashed line is the cost difference of the inter|(no WPAN) scheme to the inter|WPAN scheme, i.e., $\sum F_{inter}(\cdot|(\text{No WPAN})) - \sum F_{inter}(\cdot|\text{WPAN})$. The figure shows that the other two schemes always pay higher cost than the proposed inter|WPAN scheme since the cost difference is always larger than zero. The proposed inter-domain scheme can save up to 99.8% and 47.3% cost compared to the intra|(no WPAN) scheme and the inter|(no WPAN) scheme, respectively. The results indicate that the inter-domain cooperative resource management scheme is more cost-efficient for a WLAN/WPAN interference environment.

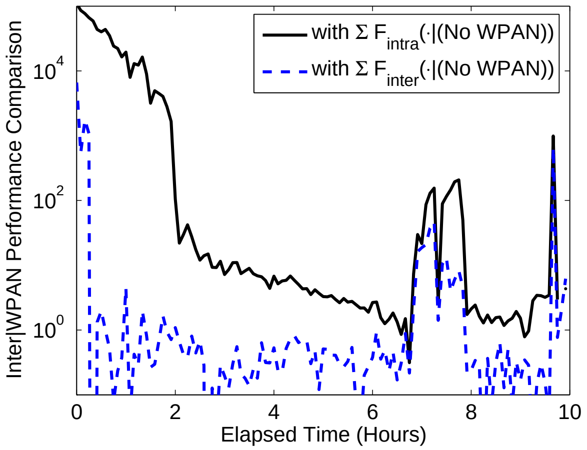

Fig. 1.10. Cost difference of intra-domain optimization without I_e to inter-domain optimization with I_e as well as inter-domain optimization without I_e to inter-domain optimization with I_e.

1.4. Decentralized WLAN Resource Management Using Multi-Agent Systems

The centralized architecture often has the single-point failure and scalability problem. In order to achieve managing resources fairly among multiple WLANs through a fully decentralized way, a multi-agent system-based approach is proposed to achieve information sharing and decision distribution among multiple WLANs in a distributed manner. WLAN providers may set up service-level agreements among themselves on how much data can be exchanged among agents. Compared to using a centralized controller, a multi-agent system-based approach is more scalable.

1.4.1. *Multi-Agent-Based Architecture*

We propose a resource management architecture for multiple WLANs using multi-agent systems, as shown in Fig. 1.11. Multiple WLANs are co-located within a particular geographic area. Communications inside the surrounding WPANs such as Bluetooth networks and WSNs generate interference to WLAN activities. An agent is located inside each AP within each WLAN and interacts with agents within its neighborhood. An agent's neighborhood consists of those agents with whom it has frequent interactions. These interactions include sharing of data and negotiating about resource assignments. Individual agents act as radio resource coordinators and cooperate with agents in their neighborhood to take care of resource management across multiple WLANs.

The agent at each AP collects the statistics from the measured operational environment as well as its neighborhood and estimates the required parameters for optimizing system performance based on predictive models. The agents use the measured data to generate local control decisions and try to optimize the performance of the entire WLAN system in a distributed fashion through agent interaction and coordination.

Agent interaction is an essential aspect of this architecture. Agent interaction occurs on the backbone network connecting all the APs. Therefore, the bandwidth requirement for agent interaction is not a critical issue. However, since multiple agents contribute to the control of optimal resource allocation across WLANs, they need to decide what information should be exchanged among neighbors, how often to exchange this information, and which neighbors should act as relay nodes for the data. When a control decision is made, an agent also needs to decide what actions its effector should take and how the control decision should be distributed to the desired area.

1.4.2. *Framework of Predictability-Based Resource Management*

Fig. 1.12 presents a block diagram of a general framework for physical environment prediction and resource management using agent technologies. The major functional blocks are: WLAN and WPAN cluster, RF

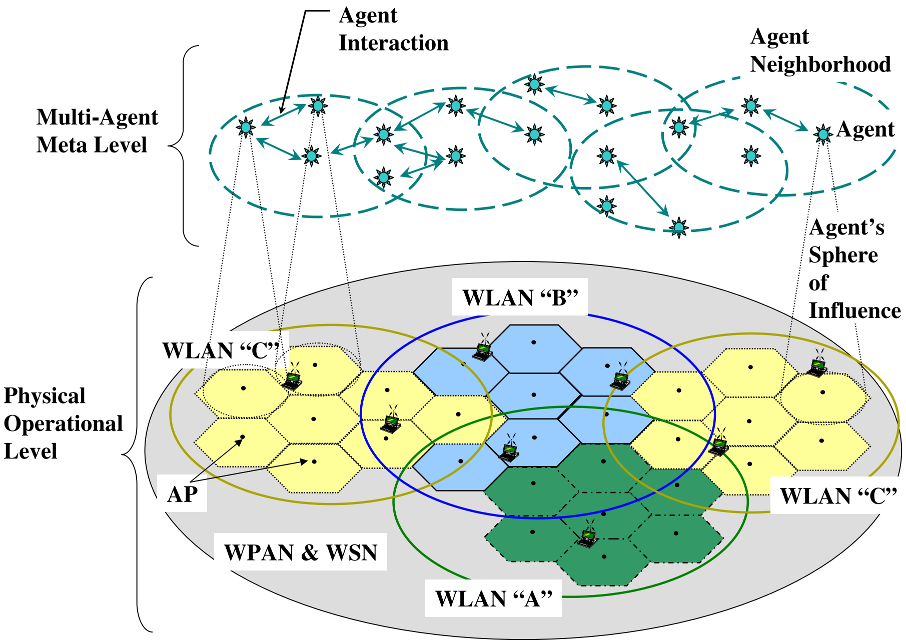

Fig. 1.11. Architecture of decentralized WLAN resource management using multi-agent systems.

environment sensing (RES), and agent operations which include predictive parameter estimation (PPE) and resource management optimization. They are explained in detail as follows.

- **WLAN and WPAN Cluster:** Each MS in WLANs operates within a dynamic RF environment comprising time-varying co-channel interference sources and time-varying interference sources from co-located WPANs. The agent inside each AP periodically collects measured statistics from the dynamic RF environment required for resource management.
- **RF Environment Sensing (RES):** This block is used to provide estimates of the signal characteristics from both MSs within the WLAN cluster as well as potential interference sources within the operational environment. Part of the functions defined in this block can be provided by the specifications of IEEE 802.11k radio resource measurement [30]. Statistics related to WPAN environmental interference levels should be provided from an additional sensing component inside each AP. Mea-

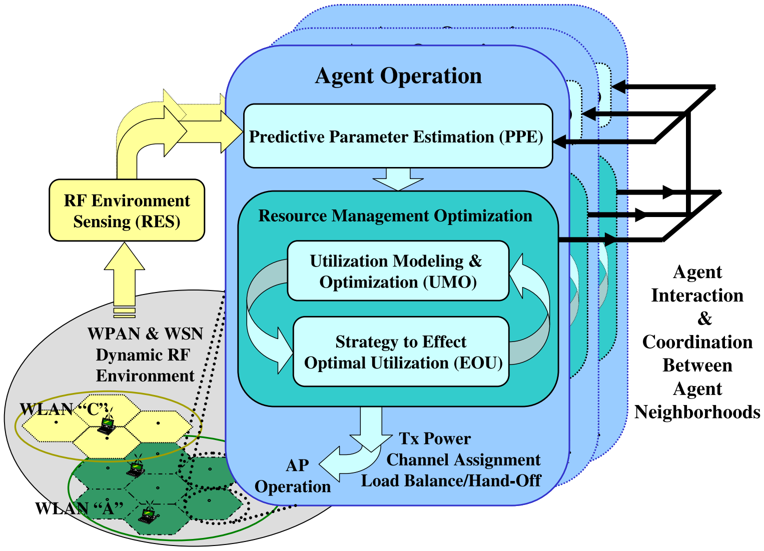

Fig. 1.12. Block diagram of physical environment prediction and agent operations.

surements would be targeted at capturing large-scale changes in signal characteristics due to variations in shadowing, MS mobility, interference sources, and interference locations. In other words, the RES needs to measure the factors which influence the resource management of the WLAN performance.

- **Agent Operation — Predictive Models for Parameter Estimation (PPE):** Estimates of signal characteristics are input to the agent inside each AP. An agent also receives data from its neighborhood through agent interaction and coordination. The general concept for the PPE block is to use predictive models to generate parameter estimates required by the resource management optimization. The parameters to be estimated include:

(a) ***Link Quality:*** link quality between each MS and its AP.
(b) ***Link Quality Rate:*** rate of changes in the expected link quality between each MS and its AP.
(c) ***Throughput:*** throughput for each WLAN cell based on the operational environment characteristics, current offered traffic, and projected offered traffic.
(d) ***Transmission Latency:*** expected time delay and the variance in the transmission time delay between each MS and its AP.

  (e) ***Handoff Latency:*** expected probability distribution of the time delay required for an MS to be handed off from one AP to another.

- **Agent Operation — Resource Management Optimization:** This block analyzes the parameter estimations and makes instructional decisions to optimize the overall WLAN performance based on designed optimization models. Instructional decisions include the optimal transmit power at APs, the optimal channel APs should operate in order to minimize interference levels and make the best use of overall resources, whether or not to accept association requests from specific MSs, whether to direct specific MSs to be associated to another AP for load balancing, and so on. These decisions are updated periodically in order to address changes in the traffic load and interference environment. They should target long-term performance improvement. The operational changes are downloaded to the WLAN cluster with the help of agent effectors and distributed to the neighborhood of agents through agent interaction and coordination.

  Resource management optimization includes two components:

  (a) **Utilization Modeling and Optimization (UMO):** This block finds the optimal utilization, i.e., the maximum allowable throughput, of each AP based on the environmental information agents possess. The decision of the optimal utilization is used by the EOU block (which is explained in the following) to generate specific strategies to achieve the optimal utilization at each AP.
  (b) **Strategy to Effect Optimal Utilization (EOU):** Given the optimal utilization of each AP, instructional decisions are generated to achieve the optimal utilization while minimizing interference to the environment. Operational changes are negotiated within the agent's neighborhood and applied to the WLAN cluster. They are also fed back to the UMO block to update the optimal utilization decision.

1.4.3. *Predictive Models for Parameter Estimation*

The predictive parameter estimation (PPE) models provide an intelligent interface between the operational environment and the resource management optimization algorithm. The PPE uses observations from both the RES and APs within an agent's neighborhood. These observations are used in conjunction with a fundamental understanding of WLAN operations to extract necessary information concerning the time-varying signal characteristics and the impact of interference on WLAN operational parameters.

The outputs of these predictive models are then utilized in the development of resource management schemes described in the next section.

A conceptual approach for implementing the PPE is illustrated in Fig. 1.13. The approach is based on using a set of integrated analytical models which utilize input from the RES and the agent interaction to estimate the dynamically varying control signals. The PPE includes analytical models to predict the current and near-term impact of the channel, MS trajectory, handoff latency, interference, and network traffic. In order to ensure that the control signals are being adequately estimated, the initial set of parameters used to optimize the control signals are intentionally selected to be extensive and inclusive. As introduced in Section 1.4.2, the initial set of parameters is given by $\mathbf{U_{ij}^T} = [L_{ij}\ R_{ij}\ S_{ij}\ T_{ij}\ H_{ij}]$, where $\mathbf{U_{ij}}$ is the MS profile for the ith MS and the jth AP and it is defined for all MSs and APs within an agent's neighborhood, including the AP with which the MS is associated. The parameters in the profile are: L_{ij} — link quality, R_{ij} — link quality rate, S_{ij} — throughput, T_{ij} — transmission latency, and H_{ij} — handoff latency.

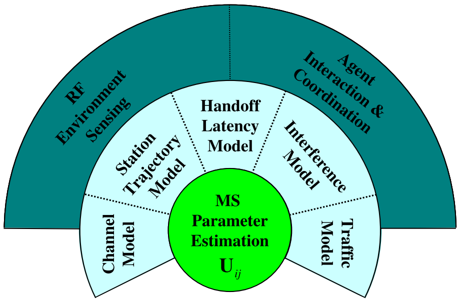

Fig. 1.13. Conceptual diagram for the PPE approach.

The analytical models required for the PPE are built upon established models reported in the literature for the channel model [37–41], the station trajectory model [42], and the traffic model [19, 32, 33]. The interference model is one of the critical components of the PPE. As derived in [3], the parameters in $\mathbf{U_{ij}}$ are dependent on the interference environment where the WLAN is operating. According to [3–6, 43–48], coexistence analysis is based on evaluating the probability of collision, $Pr[C]$. Analytical models derived in [3–6, 43–48] are central to evaluating $Pr[C]$ and are also partially explained in Section 1.3.3.2 when deriving the interference from Bluetooth to WLANs under the third-party-based centralized architecture.

The building layout in Fig. 1.14 is used to illustrate the operation of the PPE and the interaction between the various analytical models. Based on the RF propagation characteristics within the building, both APs depicted in the figure can provide service to an MS located at almost any point within the building layout. In addition to the WLAN, Bluetooth piconets are located throughout the building and will impact the WLAN activities depending on the $Pr[C]$. The shading in the figure represents the likelihood that the AP_1's signal received at an MS will be corrupted by Bluetooth interference. The $Pr[C]$ varies from 0 to 0.50. For example, at $Pr[C] = 0.25$, on average every fourth packet needs to be retransmitted in order to successfully transmit the packet. The agent within AP_1, estimates the MS's $Pr[C]$ based on observations on Bluetooth piconet activities provided by the RES and based on an estimate of the MS's location. As illustrated in the figure, using AP_1's PPE $Pr[C]$ estimate for MS_1, the set of parameters $\mathbf{U_{11}}$ can be predicted. In addition, due to the proximity of AP_2, $\mathbf{U_{12}}$ can be provided to AP_1 through agent interaction. Furthermore, using the directional estimate for MS_1, a time sequence for $\mathbf{U_{11}}$ can be estimated by AP_1's PPE with a corresponding confidence interval provided for each estimate. The PPE can therefore provide a powerful tool for enhancing the resource management optimization process.

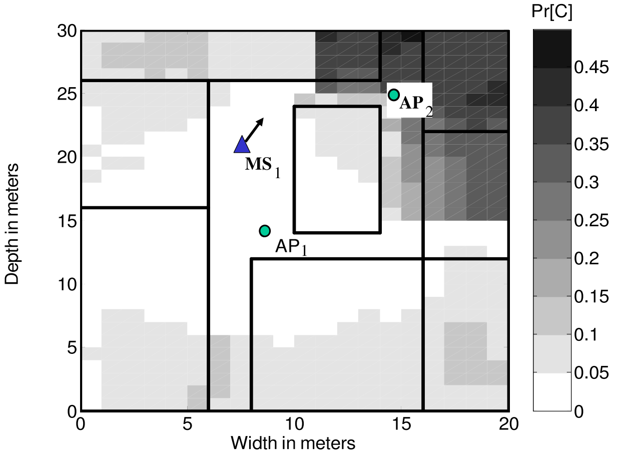

Fig. 1.14. $Pr[C]$ analysis results overlaid onto the floor layout based on a specific Bluetooth interference profile.

The estimations of $\mathbf{U_{ij}}$ based on the PPE approach is outlined as follows.

Link Quality, L_{ij}, estimated based on the expected packet error rate,

$E[PER]$, of the link between the ith MS and the jth AP. As derived in [3], in an interference environment, $E[PER] = Pr[C]$. Given multiple interference sources with corresponding $Pr[C_i]$ and assuming the interferences are independent, $E[PER] = \sum Pr[C_i] - \sum \sum_{i \neq j} Pr[C_i]Pr[C_j] + \cdots$.

Link Quality Rate, R_{ij}, estimated based on the expected rate of change in L_{ij}. As illustrated in the example above, the station trajectory model, channel model, and interference model are used in estimating the rate at which the link quality changes. The station trajectory model is used to estimate of the direction and rate of movement for the MS, which can be estimated using a similar approach presented in [42].

Throughput, S_{ij}, detailed analytical models for evaluating the throughput for IEEE 802.11 CSMA/CA-based medium access control (MAC) have been developed in [49, 50]. In [49], the proposed analytical throughput model is based on a two-dimensional Markov chain which takes into account the probability of collision for MSs. We have extended this model to take into consideration the effect of co-channel interference on the analytical throughput in WLANs with multiple co-channel cells [51]. In addition, we can also extend the throughput model to include $Pr[C]$ due to interference from sources other than 802.11 transceivers. It is similar to the Markov model developed in [52] to evaluate packet transmission latency. Therefore, a complete analytical representation of WLAN cell throughput considering different interference sources can be developed. In addition to the channel, station trajectory, and interference models, the traffic model will also play a key role in estimating the throughput.

Transmission Latency, T_{ij}, a first-order approximation for the expected packet transmission latency is derived in [3], $E[T] = T_{normal}\left(1 + \alpha Pr[C]\right)\left(1 - Pr[C]\right)^{-1}$, where T_{normal} is the time required to transmit a packet given no interference and α is a proportionality constant relating the T_{normal} to the time required to retransmit a packet, αT_{normal}. In addition, a more detailed analytical expression for expected packet transmission latency has been derived in [52], which is based on a more accurate model of the IEEE 802.11 back-off algorithm.

Handoff Latency, H_{ij}, we have conducted research on setting up an analytical model for handoff latency analysis based on IEEE 802.11b medium access control scheme [53]. This model considers comprehensive factors which influence the WLAN handoff latency such as medium access collision probability, binary exponential back-off latency, packet transmission delay, queuing delay at APs, and so on as well as the range these factors affect the handoff latency. The outcome of this research is the probability distribution of the handoff latency in a certain range based on the offered traffic load and network conditions in the WLAN. Therefore, from this research, we can predict the likelihood the handoff can be finished at a certain moment.

1.4.4. *Resource Optimization Using Multi-Agent Systems*

1.4.4.1. *Overview of Resource Management Optimization*

The goal of the utilization modeling and optimization (UMO) block is to adjust resource allocation in each WLAN in order to minimize the total system cost. Based on the optimal utilization for each AP derived from the UMO, the strategy to effect optimal utilization (EOU) block inside each agent generates corresponding strategies to satisfy the optimal utilization requirement for each cell. These strategies include instructing the APs on which channels they should operate, which transmit powers they should use, whether or not to accept association requests from specific MSs, and so on. These actions are needed to make dynamic channel allocation, dynamic transmit power control, and load balancing possible, which can be expected to significantly improve the performance of multiple WLANs [16]. In this research, we focus on dynamic load balancing, i.e., finding the optimal set of MSs under each AP and instructing specific MSs with which AP they should be associated. The association control from the EOU helps re-distribute loads across neighboring APs by requesting MSs to explicitly change their association from an overloaded AP to a less loaded neighboring AP so that no one AP is unduly overloaded.

In a distributed implementation, the multi-agent system directs the APs to re-distribute associations of MSs. MSs that are re-distributed perform handoffs to a new AP. The re-distribution process considers the optimal allowable throughput S^* of each AP, which is calculated in order to minimize the overall cost in the agent neighborhood. Each agent negotiates with other agents in its neighborhood to decide which MS should be handed off to a neighboring AP; when to initiate the handoff; and when to complete the handoff. This coordination among neighboring agents will result in event triggers which indicate the need to balance the traffic load based on a distributed constraint optimization algorithm. The result of applying such an optimization algorithm is an optimal handoff strategy, i.e., the EOU strategy.

Distributed Constraint Optimization Problems (DCOPs) have been used as fully distributed algorithms to solve existing centralized problems efficiently [9, 10]. In the following discussion, we first present a model based on a multi-agent DCOP to illustrate our distributed approach to dynamic load balancing.

1.4.4.2. *Scenario of WLAN Handoffs for Load Balancing Using DCOP Algorithm*

A discrete multi-agent DCOP [11] is a tuple $\langle A, X, D, R\rangle$, where

- $A = \{A_1, \ldots, A_n\}$ is the set of agents interested in the solution; in the WLAN context, each access point AP_i is assigned an agent.
- $X = \{X_1, \ldots, X_m\}$ is the set of variables; in the WLAN context, each AP_i has a variable X_i for MS_i, which represents the new associated AP_j after a handoff.
- $D = \{d_1, \ldots, d_m\}$ is a set of domains of the variables, where each domain d_i is the set of APs in AP_i's neighborhood.
- $R = \{r_1, \ldots, r_p\}$ is a set of relations where a relation r_i is a utility function which provides a measure of the value associated with a given combination of variables. In WLANs, R represents objective functions, which are provided by the UMO block in Fig. 1.12. They are similar to (1.3) shown in the centralized implementation.

We describe a simple WLAN scenario, as shown in Fig. 1.15 to explain how to use the DCOP algorithm for WLAN load balancing. In this scenario, three APs are depicted in the figure at $(x,\ y)$ locations AP_1: (0, 0); AP_2: (45, 90); AP_3: (90, 0). In addition, there are three MSs depicted in the figure. The MS_1 remains stationary at location (-45, -45) during the five-second duration of the simulation from t_0 to t_5. MS_2's location at t_0 is at (20, 55) and moves in the x-direction at 5 meters per second. MS_3's location at t_0 is at (75, 87) and moves in the negative y-direction at 3 meters per second.

The goal of the DCOP algorithm is to dynamically assess the MS associations with the APs at time t_k based on the estimate of the state of the MSs at time t_{k+1} where $t_H = t_{k+1} - t_k$ is the fixed time required to handoff an IEEE 802.11 MS from one AP to a neighboring AP. For simplicity, for the simulation shown below, the handoff latency, t_H, is an expected value and $t_H = 350$ ms corresponding to the expected handoff latency associated with the standard IEEE 802.11 protocol [54].

For the purpose of this example, the state of the MSs within a WLAN is defined by two parameters: the AP utilization and the link quality between

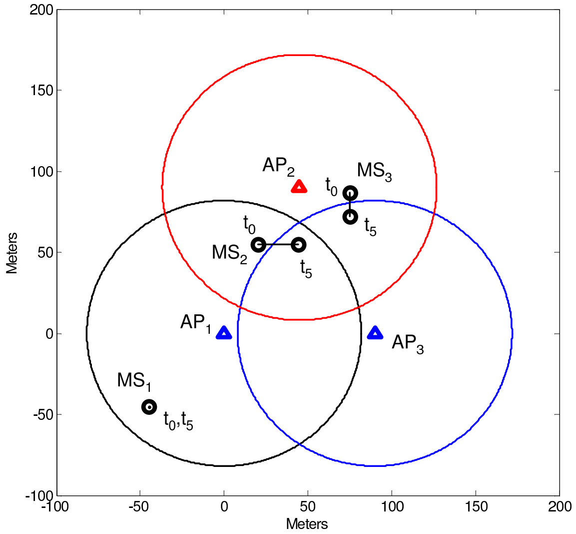

Fig. 1.15. Scenario for illustrating the DCOP algorithm for WLAN load balancing.

the MS and AP. The AP utilization is based on the number of MSs associated with it during time interval t_H. Based on the current IEEE 802.11 protocol, each MS can only be associated with a single AP. Therefore, the association between AP_j and MS_i at time t_k is given by

$$\rho_{ij}(t_k) = \begin{cases} 1. & AP_j \text{ and } MS_i \text{ are associated at time } t_k \\ 0, & AP_j \text{ and } MS_i \text{ are not associated at time } t_k \end{cases} \tag{1.22}$$

Assuming the traffic offered by each MS is on average the same, then the AP utilization is estimated by

$$\rho_j(t_k) = \sum_{i=1}^{M} \rho_{ij}(t_k), \tag{1.23}$$

where M is the total number of MSs within the WLAN.

The link quality is based on the expected received power over a transmission distance of $d_{ij}(t_k)$ between AP_j and MS_i at time t_k given by

$$P_R(d_{ij}(t_k)) = P_T - (20\log_{10} f_c + 10n\log_{10}(d_{ij}(t_k)) - 28)\,(\text{dBm}), \tag{1.24}$$

where P_T is the WLAN transmit power, $P_T = 20$ dBm; f_c is the WLAN carrier frequency, $f_c = 2.4$ GHz; n is the pathloss exponent, $n = 3$; $d_{ij}(t_k)$ is the Euclidean distance between AP_j and MS_i at time t_k. In the figure, the boundary for each AP's coverage range is depicted as a circle around the AP based on the power received threshold, γ, of -82 dBm.

The received power by MS_1 from the three APs remains constant over the duration of the simulation and are [-78.7, -90.9, -89.2], respectively for $[AP_1, AP_2, AP_3]$. The received power by MS_2 and MS_3 from each of the APs changes continuously over the 5 second scenario based on the mobility profile for each MS. The corresponding received power versus the scenario time is illustrated in Fig. 1.16 and 1.17.

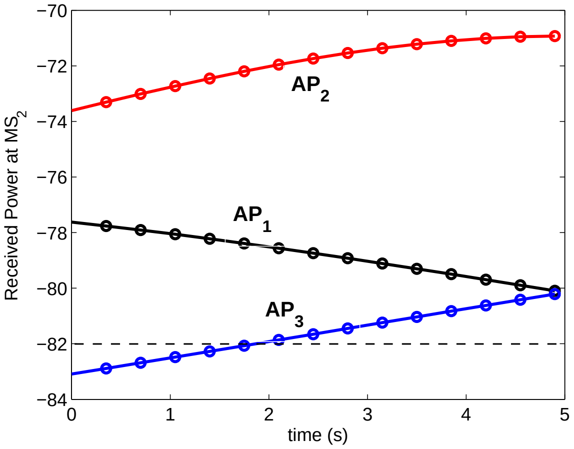

Fig. 1.16. Received power at MS_2.

For the scenario described above, suppose each access point AP_i is represented by an agent A_i. Each MS_j is initially associated with an AP_i at time t_k. Each AP_i has a variable X_i for MS_i, which represents the new association AP_j at time t_{k+1}. Hence, X_i is equivalent to $\rho_{ij}(t_{k+1})$ defined in (1.22). At any point in time, only a subset of the agents will be involved in the resource-allocation process, which means that the multi-agent system is constructed dynamically. Periodically, each agent listens to handoff event triggers. The event triggers for handoffs are usually requested from MSs need to be handed off or when an AP is overloaded. They initiate agent local computations and communications with other agents in the neighborhood to handle the resource-allocation problem.

The DCOP is viewed as an optimization problem with the following criteria:

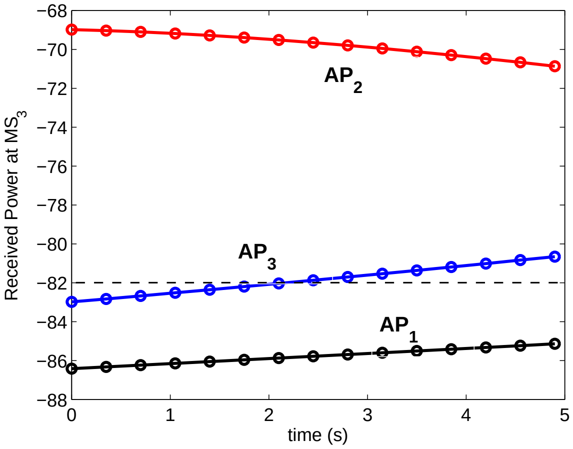

Fig. 1.17. Received power at MS_3.

Criterion I: Maximize the utilization of each AP in order to accommodate more users, i.e.,

$$\begin{aligned} &\text{Maximize} \;\; \rho_j(t_{k+1}) \\ &\text{Subject to} \;\; P_R(d_{ij}(t_{k+1})) > \gamma, \quad \forall i, j | \rho_{ij}(t_{k+1}) = 1 \end{aligned} \tag{1.25}$$

Criterion II: Maximize the minimum received power by each MS in order to improve the link quality and minimize the likelihood of packet loss, i.e.,

$$\text{Maximize} \min_{i,j|\rho_{ij}(t_{k+1}=1)} (P_R(d_{ij}(t_k))) \tag{1.26}$$

Criterion III: Distribute the load amongst viable APs in order to increase fairness as well as increase the overall system-wide utilization, i.e.,

$$\text{Minimize} \max_{j,l} (|\rho_j(t_{k+1}) - \rho_l(t_{k+1})|) \tag{1.27}$$

Criterion IV: Each MS can only be assigned to one AP at any time according to the current IEEE 802.11 standard, i.e.,

$$\sum_j \rho_{ij} = 1 \tag{1.28}$$

We describe a simple distributed algorithm to solve the DCOP which will specifically consider the handoff process at three time slots: $t_k = 0$, the start time; $t_k = 1.75$, when MS_2 crosses the boundary of AP_3; and $t_k = 2.45$, when MS_3 crosses the boundary of AP_3. We assume that for each of the three time slots, the MS_is have the following initial association: MS_1 is associated with AP_1, MS_2 and MS_3 are both associated with AP_2. The destination APs computed by the decision process described below are independent of the agent performing the computation.

1.4.4.3. *Time* $t_k = 0$

Each agent A_i inside AP_i will identify all values for the variable X_i that satisfy criterion I, II, III,and IV. Criterion I and II can be verified locally within an agent, while criterion III requires communications with other agents about their respective assignments in order to determine the load of the APs.

Agent A_1 (at access point AP_1) computes the value assignment for X_1 to be AP_1, as it is the only AP from which the power received is greater than γ (-82 dBm). Criterion II is consistent with this value. Agent A_2 (at access point AP_2) computes the value assignment for X_2 to be $\{AP_1, AP_2\}$ as the power received from each of the two APs is greater than γ. Criterion II would lead to X_2 being assigned AP_2 as it maximizes the minimum power received. Agent A_3 (at access point AP_3) computes the value assignment for X_3 to be AP_2 as it is the only AP from which the power received is more than γ. Criterion II is consistent with this value. In order to verify criterion III, the agents exchange their assignment information and independently compute the load information. Although AP_2 has both MS_2 and MS_3 associated with it and AP_3 has none associated with it, this is determined to be a fair load since a reassignment of either MS_2 or MS_3 to AP_3 would cause criterion I to be violated. Criterion IV is consistent with this assignment.

Hence the final assignment at time $t_k = 0$ is $X_1 = AP_1$; $X_2 = AP_2$; $X_3 = AP_2$.

1.4.4.4. *Time* $t_k = 1.75$

Agent A_1 computes the value assignment for X_1 to be AP_1, as it is the only AP from which the power received is greater than γ (-82dBm). Criterion II is consistent with this value. Agent A_2 computes the value assignment for X_2 to be $\{AP_1, AP_2\}$ as the power received from each of the two APs is greater than γ. Criterion II would lead to X_2 being assigned AP_2 as it maximizes the minimum received power. Agent A_3 computes the value assignment for X_3 to be AP_2 as it is the only AP from which the power received is more than γ. Criterion II is consistent with this value. In order to verify criterion III, the agents exchange their assignment information and independently compute the load information. Although AP_2 has both MS_2 and MS_3 associated with it and AP_3 has none associated with it, this is determined to be a fair load since a reassignment of either MS_2 or MS_3 to AP_3 would cause criterion I to be violated. Constraint IV is consistent with this assignment.

Hence the final assignment at time $t_k = 1.75$ is $X_1 = AP_1$; $X_2 = AP_2$; $X_3 = AP_2$.

1.4.4.5. *Time* $t_k = 2.45$

Agent A_1 computes the value assignment for X_1 to be AP_1, as it is the only AP from which the power received is greater than γ (-82dBm). Constraint II is consistent with this value. Agent A_2 computes the value assignment for X_2 to be $\{AP_1,\ AP_2,\ AP_3\ \}$ as the power received from each of the three APs is greater than γ. Criterion II would lead to X_2 being assigned AP_2 as it maximizes the minimum received power. Agent A_3 computes the value assignment for X_3 to be $\{AP_2,\ AP_3\}$ as the power received from both APs is more than γ. Criterion II would lead to X_2 being assigned AP_2 as it maximizes the minimum received power. In order to verify criterion III, the agents exchange their assignment information and independently compute the load information. AP_2 has both MS_2 and MS_3 associated with it and AP_3 has none associated with it. Using simple backtracking, it is determined that the AP utilization is best optimized for all three criteria when X_2 is reassigned to AP_3 (power received is -69.6505 dBm) and X_3 retains its association with AP_2 (power received is -81.6561 dBm). Criterion IV is consistent with this assignment.

Hence the final assignment at time $t_k = 2.45$ is $X_1 = AP_1$; $X_2 = AP_3$; $X_3 = AP_2$.

1.5. Conclusion

In this chapter, a framework for resource management across multiple WLANs in interference environments is introduced. The framework is based on multi-agent systems for decentralized information sharing and network management decision-making. It emphasizes the predictability of the time-varying network states using predictive models and incorporates the impact of interference into the resource optimization. A centralized resource optimization approach under a third-party-based architecture is first explained. The performance of the centralized approach is used as the performance benchmark for the proposed decentralized approach. Then, the functional details of each component under the multi-agent system-based decentralized architecture are introduced. A handoff scenario is used to explain how to use a DCOP algorithm, a fully distributed algorithm based on the multi-agent system, to make the handoff decisions for load balancing. This chapter is aimed at conveying to the research community the importance of cooperative network management for multiple WLANs and introducing a novel decentralized network control framework suitable for large-scale networks in interference environments.

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