Joint Handoff and Resource Management in Wireless Mesh Networks

JOINT HANDOFF AND RESOURCE MANAGEMENT IN WIRELESS MESH NETWORKS

BY

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This thesis is dedicated to my parents and grandma

for their love, endless support and encouragement.

Abstract

In this thesis we study the handoff problem of mobile stations (MSs) jointly with the resource management at the access points (APs) for wireless mesh networks (WMNs), where the APs can dynamically adjust the transmission power and time to each of the associated MSs. Two objectives are considered, one is to balance the energy consumption of the APs, and the other is to achieve fair throughput among the MSs. Since the global optimum solutions are difficult to obtain, we propose heuristic schemes for achieving each of the objectives.

The objective of balancing AP energy consumption is achieved in two steps. The optimum transmission power and rate is solved at each AP so that to minimize the energy consumption of the AP, assuming the MS-AP association is given. Two handoff schemes are then designed to find which MSs should be associated to which APs during each scheduling interval (SI). The schemes are based on energy consumption information exchanged among neighboring APs. The real-time energy balancing (REB) scheme tries to balance the energy consumption of the APs in each SI, while the long term energy balancing (LEB) scheme balances the AP energy consumption over a longer term. Our results indicate that the network lifetime can be significantly extended using the proposed handoff schemes, compared to the simple distance-based handoff scheme, and using LEB can achieve balanced AP energy consumption with

a small number of handoffs.

The second part of the thesis is to consider the MS handoff and AP resource allocations in order to achieve fair throughput among the MSs. An optimization problem is formulated and solved at each AP to achieve long term proportional fairness of the throughput among the MSs, assuming the MS-AP association is known. Two handoff schemes are proposed, one is utility-based, and the other is number-based, in order to determine which MSs should be associated to which APs. Our results show that both the schemes are good at achieving fair throughput among the MSs, and the schemes are not sensitive to MS moving speed or group mobility patterns. The number-based scheme is simpler than the utility-based one in terms of implementation.

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Last but not least, I would like to show my grateful thanks to my parents for everything they do for me.

List of Abbreviations

WMN	Wireless Mesh Network
AP	Access Point
MS	Mobile Station
QoS	Quality of Service
MAC	Medium Access Control
SI	Scheduling Interval
PF	Proportional Fairness
SNR	Signal-to-Noise Ratio
GM	Group Mobility
REB	Realtime Energy Balancing
LEB	Longterm Energy Balancing

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Chapter 1

Introduction

1.1 Handoff Management in Wireless Mesh Networks

Wireless mesh networks (WMNs) have been widely deployed because of their flexibility and low cost. In contrast to pure ad hoc networks, WMNs having an infrastructure formed by fixed access points (APs) provide relatively reliable transmissions for forwarding data to and from mobile stations (MSs). The fixed infrastructure also provides chances for better utilizing the radio resource and improving the network performance. WMNs are typically deployed in office buildings, campus, and communities, where most users are static or have low mobility. Recently, WMNs have gained significantly more attention in academia and in the standardization groups, e.g., [1, 2, 3, 4], to provide services for vehicles along the road, where the users can be highly mobile. As a result, mobility and handoff management becomes very important in such networks in order to provide satisfactory quality of services for the users, while optimizing the network performance in different aspects.

Various performance metrics should be considered when designing a WMN. For example, each user may require a certain throughput; and the service quality among different users should be fair. For the network service providers, the radio resources should be utilized efficiently by serving more users with satisfactory service quality. For APs powered by batteries, energy consumption can be an important issue to be considered. Some special issues should be considered when designing a WMN with mobile users. In particular, mobility and handoff of the users affect not only the service quality of individual users, but also the overall network performance. In the next section, some work related to handoff management in WMNs is briefly reviewed.

1.2 Related Work

A lot of the current WMNs are based on IEEE 802.11. The traditional IEEE 802.11 standards do not allow power control at the APs. That is, an AP either transmits at the full power or does not transmit (it may switch to a power saving mode, at which mode the AP consumes much less power than in the normal work mode). Because of the fixed transmission power, MSs close to the coverage boundary of the AP may receive very low signal strength from the AP, and this results in poor service quality to the MSs. If the transmissions use adaptive modulation and coding, these MSs may be served at very low instantaneous rates. As a result, a very long transmission time is required from the AP in order to provide the MSs with a certain transmission throughput. This can significantly degrade the service throughput to other users or reduce the capacity of the AP [5, 6].

Another problem is that the deployment of the APs in most WMNs is not carefully planned due to the complexity of the radio signal propagation, especially in indoor environments. In a lot of cases, the coverage of the AP can terminate very abruptly, such as near the building gates. When the APs are installed within buildings and a user is moving from inside the building to the outside, the service to the user can stop without a transitional period. Therefore, a lot of work has been done to detect the coverage changes before the link conditions drop significantly and to make proactive handoff decisions. In [7], an AP selection method is proposed by considering the wireless link conditions based on the number of frame retransmissions. The basic idea is that the number of retransmissions increases as the link conditions become worse. In [8], a hybrid dynamic association approach is proposed for WMNs, where a user first chooses to associate to the AP offering the maximum throughput, and later can change to associate to the AP providing the maximum signal strength if a measure of available bandwidth from its current associated AP drops below a certain threshold. In [9] a base station location optimization problem is described for UMTS networks, in which the demand node maps and the target base station sites are known beforehand. The problem of cost-optimal placement of the energy sustainable nodes is considered in [10], so that a significant improvement in cost can be obtained using the proposed methodology.

For the mobile users, service continuity should be well maintained throughout the lifetime of their connections, during which the MSs may have to handoff between different APs as they move around. In the traditional IEEE 802.11-based WMNs, performing handoffs requires considerable signaling overhead, which can cause long delay. Various work has been done to reduce the handoff delay and achieve fast handoff, and some examples can be found in [11, 12, 13]. In [11], an architecture is designed with both the parallel handoff execution and data caching mechanism, which offers a seamless handoff for supporting real-time applications. In [12], the authors utilize a spatiotemporal graph to provide spatiotemporal information for making accurate handoff decisions by correctly searching for the next AP.

Performing handoff takes time and can cause link interruptions. Some work has been done to minimize packet losses during handoff and to achieve smooth handoffs. In [14], the authors design a caching framework so that data can be buffered both in the current route of the flow and in the neighboring nodes. This increases the availability of data during handoff. Another approach can be found in [15], which relies on a notification scheme during handoff in order to guarantee the packets to be delivered from one MS to anther.

The decision to make a handoff can be simply based on distance or received signal strength, and the MSs can select the nearest AP or the AP that provides the best signal strength, if the objective is for the MSs to get connected to the AP. Handoffs can also be used to balance the traffic loads among the APs, such as in [16, 17, 18]; or to provide better and fair services to the users, such as in [19, 20].

In addition to what mentioned above, handoffs can also affect other aspects of the WMNs. In this thesis, we consider handoff management jointly with energy consumption of the APs and throughput fairness to the MSs.

1.3 Motivation of the Thesis Work

A lot of the APs in future WMNs will be battery or solar battery powered either due to the difficulty to access to the wired electricity or to make the network environment friendly. Energy saving of the APs becomes one of the main concerns in future

WMNs in order to continuously serve the MSs. One method is to allow the APs to operate in a low power mode, such as switching to a sleep mode, for as much time as possible. This introduces delay for the APs to react to network condition changes. How to reduce the delay for performing handoffs while maximizing the AP sleep time is studied in [21].

Adaptively adjusting the AP transmission power allows the AP to transmit only the minimum power necessary in order to satisfy the service requirements of the MSs. Examples of the WMNs that apply power control at the APs can be found in [22, 23, 24]. The purposes for power control include extended battery life, better channel efficiency, better throughput, and etc.. Adaptively adjusting the transmission power of the APs can bring a lot of other benefits as well as challenges to both the network and individual MSs.

(1) By adjusting the AP transmission power, the transmission distance of the AP can be extended or shrank. Therefore, transmission power of the AP can be determined based on the MS locations and transmission conditions, and this brings flexibility for the MSs to associate to different APs, which may provide further flexibility to improve the network performance, such as capacity, throughput to individual MSs, and fairness. On the other hand, optimizing the network performance in such an environment becomes very complicated, because there is no central station available to coordinate among different APs.

(2) The instantaneous service rate to the MSs can be changed by varying the transmission power of the AP. Given the MS's current link conditions, a higher transmission power from the AP can provide the MS with higher transmission rate, which may be translated into shorter transmission time from the AP, if

the total throughput required by the MS is fixed.

Based on the above discussions, we consider the handoff and resource management problem jointly in a WMN from two perspectives. The first is to balance the energy consumption of the APs; and second is to provide fair throughput to the MSs.

For a network with multiple APs, the service continuity of the network is determined by the AP with the shortest lifetime. In order to balance the energy consumption of different APs, an AP with more residual energy can have more MSs associated to it and transmit at high power to the MSs further away from it. On the other hand, an AP with little energy available should transmit to fewer MSs close to it. This makes the actual coverage area of each AP to vary with the network conditions, and therefore, traditional handoff criteria, such as the ones based on the MS-to-AP distance or pilot signal strength are not suitable in such a scenario. Although transmission power and rate adaptation has been extensively studied in WMNs, little work is available to study MS handoff in order to balance and minimize the energy consumption of the APs.

In a WMN with a large number of MSs, the service quality to the individual MSs depends on their respective link conditions. Providing fair services among all the MSs can be difficult. For a typical example, the MSs near the APs may receive higher throughput than those further away from the APs. Another example is that the MSs in the coverage area of an overloaded AP receive poorer service quality than those in the coverage area of a lightly loaded AP. Performing handoff to the MSs can possibly balance the traffic load of the APs so that to achieve fair service quality to the MSs located at different positions.

One of the main difficulties to perform the optimum handoff and resource management is that the WMNs do not have a central station to coordinate the decisions among the APs and among the MSs belong to different APs. Therefore, the resource allocations, such as transmission power and time to each individual MS, and handoff decisions, are made locally by individual APs, while the objective is to optimize the performance of the overall network, such as to minimize the maximum energy consumption of the APs or optimize the throughput fairness among the MSs.

The format in this work is to first formulate an optimization problem for allocating resources of the APs based on the specific objectives, and then design heuristic handoff schemes based on it. It is assumed that neighboring APs can exchange some limited information about the conditions within their own coverage areas, and use this information to guide the MSs to handoff.

The remaining part of the thesis is organized as follows. In Chapter 2 we study the handoff and resource management jointly with an objective to balance the AP energy consumption. In Chapter 3 we study the handoff and resource management jointly with fair throughput scheduling. Chapter 4 concludes the thesis and discusses some future research topics.

Chapter 2

Joint Handoff and Resource Management for Balancing AP Energy

In this chapter, we study the MS handoff and AP resource allocations jointly in order to balance the energy consumption of the APs in a WMN, where the APs can dynamically adjust their transmission power and time to the MSs. The objective is to guarantee the required throughput for each MS, while maximizing the network lifetime, which is determined by the AP with the minimum amount of available energy. The global optimum solution is difficult to obtain due to that there is no central station available. The problem is solved in two steps. We formulate an optimization problem for individual APs to minimize their energy consumption based on the channel conditions of the MSs, assuming the MS-AP association relationship is known, and then design two handoff schemes to find which MSs should be associated to which APs during each scheduling interval (SI). The first handoff scheme tries to balance the energy consumption of the APs in each scheduling interval, while the second one balances the AP energy consumption over a longer term. Our results demonstrate that both schemes achieve much longer network lifetime than the traditional distance-based handoff scheme, while the long-term based handoff scheme can achieve the objective with approximately the same number of handoffs as the distance-based handoff. The remainder of the chapter is organized as follows. In Section 2.1 we describe the system model and formulate the energy optimization problem for individual APs. The handoff schemes are proposed in Section 2.2. Numerical results are demonstrated in Section 2.3, followed by a summary in Section 2.4.

2.1 Optimum AP Energy Consumption

We consider a WMN with multiple APs. MSs move at random speeds and directions within the service area of the network. We assume that transmissions at different APs use orthogonal channels and do not interfere with each other. The orthogonal channels can be either different frequency channels or different time periods of the same frequency channel. Channel time is divided into equal length scheduling intervals (SIs), each of which can be one or several superframes. We consider that the changes to the link gains between the MSs and the APs during each SI are very small and can be neglected. The MSs report the link gains to their currently associated APs at the beginning of each SI. The link gain information can also be piggybacked in the uplink data messages and used by the APs for allocating resources for the downlink transmissions in the next SI.

MSs communicate directly with their associated APs. Handoff of the MSs between different APs can only be performed at the beginning of a SI, and the association relations between the MSs and the APs are kept unchanged during each SI. All the APs have access to a common database or file server through high speed links, and can pass data to their associated MSs, each of which requires a minimum throughput η_m^* during each SI, where $m = 1, 2, \ldots, M$, and M is the total number of MSs. Let $T_{im}(t)$ represent the amount of time during which AP i transmits to MS m, $R_{im}(t)$ represent the instantaneous transmission rate of the AP to the MS, and $\mathcal{M}_i(t)$ be a set of the MSs associated to AP i, then

$$T_{im}(t)R_{im}(t) \geq \eta_m^*, \tag{2.1}$$

for all $m \in \mathcal{M}_i(t)$, where t is the index of the SI. The instantaneous transmission rate to MS m is determined by the transmission power of the AP to the MS, $P_{im}(t)$, and the link gain between the stations, $g_{im}(t)$, i.e.,

$$R_{im}(t) = \omega \log_2 \left(1 + \frac{P_{im}(t)g_{im}(t)}{P_{noise}}\right), \tag{2.2}$$

where ω is the transmission bandwidth and P_{noise} is the background noise power. The total amount of energy consumed by AP i for MS m is given by

$$E_{im}(t) = P_{im}(t)T_{im}(t). \tag{2.3}$$

From (2.1) we can find that the required throughput for a given MS can be provided either by a higher instantaneous transmission rate and shorter transmission time, or a longer transmission time and a lower instantaneous rate. If $T_{im}(t)$ is doubled, $R_{im}(t)$ is decreased by half in order to achieve the same throughput requirement. From (2.2) we can find that reducing $R_{im}(t)$ by half can further lead to an exponential decrease in $P_{im}(t)$. Therefore, in order to minimize $E_{im}(t)$ in (2.3), the AP should try to allocate the longest transmission time to each MS. Since the total transmission time of AP i in each SI is limited, resource allocations for multiple MSs associated to the same AP should be jointly optimized. Within AP i, the optimum resource allocations at SI t can be found from the following problem:

$$\text{P1.} \quad \min \ E_i(t) \tag{2.4}$$

$$\text{s.t.} \quad E_i(t) = \sum_{m \in \mathcal{M}_i(t)} E_{im}(t) \tag{2.5}$$

$$E_{im}(t) = P_{im}(t) T_{im}(t), \ m \in \mathcal{M}_i(t) \tag{2.6}$$

$$\sum_{m \in \mathcal{M}_i(t)} T_{im}(t) \leq T_{\max,i} \tag{2.7}$$

$$R_{im}(t) \leq \omega \log_2 \left[1 + \frac{P_{im}(t) g_{im}(t)}{P_{noise}} \right], \ m \in \mathcal{M}_i(t) \tag{2.8}$$

$$\eta_m^* \leq T_{im}(t) R_{im}(t), \ m \in \mathcal{M}_i(t). \tag{2.9}$$

where $T_{\max,i}$ is the total available transmission time of AP i during one SI. Because of the relationship between $T_{im}(t)$ and $P_{im}(t)$ as mentioned above, the solution to problem P1 tends to make (2.7) an equality.

Assuming that all APs have the same amount of total energy at time zero, maximizing the network lifetime is then equivalent to minimizing the maximum energy consumption of individual APs over a long term. That is,

$$\text{P2.} \quad \min \max_i \ \hat{E}_i \tag{2.10}$$

$$\text{s.t.} \quad \hat{E}_i = \sum_{t \in \mathcal{T}} \sum_{m \in \mathcal{M}_i(t)} E_{im}(t) \tag{2.11}$$

$$E_{im}(t) = P_{im}(t) T_{im}(t), \ m \in \mathcal{M}_i(t) \tag{2.12}$$

$$\sum_{m \in \mathcal{M}_i(t)} T_{im}(t) \leq T_{\max,i} \tag{2.13}$$

$$R_{im}(t) \leq \omega \log_2 \left[1 + \frac{P_{im}(t) g_{im}(t)}{P_{noise}} \right], \ m \in \mathcal{M}_i(t) \tag{2.14}$$

$$\eta_{im}^* \leq T_{im}(t) R_{im}(t), \ m \in \mathcal{M}_i(t) \tag{2.15}$$

$$\mathcal{M}_i \subseteq \{1, 2, \ldots, M\} \tag{2.16}$$

where $\mathcal{T} = \{1, 2, \ldots\}$ is a set of the SIs. The unknowns in this problem are $P_{im}(t)$ and $T_{im}(t)$ for all i, m, and t, and $\mathcal{M}_i(t)$ for all i and t. Solving problem P2, however, is impossible in practice, not only because it needs a central station to collect the link gain information, but also because it requires all link gains at future time. In this work, we solve the joint MS handoff and AP energy management problem in two steps, one is to determine $\mathcal{M}_i(t)$ at each time t, and the other is to allocate AP resources based on the solution to P1 for given $\mathcal{M}_i(t)$. The first problem becomes to make handoff decisions for individual MSs and is studied in the next section.

2.2 Proposed Handoff Schemes

In this section we design two handoff schemes. The first scheme is based on the information in the current SI and balances the energy consumption of the APs in each SI, and the second scheme uses both information in the current SI and in the past and balances the AP energy consumption over a longer term.

2.2.1 Realtime Energy Balancing Scheme (REB)

Algorithm 1 outlines this scheme performed at AP i, where the time variables are omitted to make concise presentation. At the end of each SI, each AP calculates its E_i values, which are exchanged between neighboring APs at the beginning of the next SI. Define $\mathcal{N}_i$ as a set of the neighboring APs of AP i. Upon receiving E_j's from AP j for all $j \in \mathcal{N}_i$, AP i calculates the average energy consumption of the neighboring APs as

$$\overline{E}_{\mathcal{N}_i} = \frac{\sum_{j \in \mathcal{N}_i} E_j}{|\mathcal{N}_i|}, \tag{2.17}$$

where $|\mathcal{N}_i|$ is the number of APs in $\mathcal{N}_i$. If E_i is larger than $\overline{E}_{\mathcal{N}_i}$ by a certain value ε, an indicator H_i is set to 1, and some MSs currently associated to AP i can potentially be handed off to the neighboring APs. The value ε is between 0 and 1 and used to reduce unnecessary handoffs. If ε is small, frequent and unnecessary handoffs may occur between the APs; while if ε is large, fewer handoffs are performed and the algorithm may not be able to balance the AP energy consumption.

Given ε, the number of MSs that should be handed off and which APs these MSs may be handed off to depend on specific conditions. In order to limit the implementation complexity, we consider that at most one MS can be handed off from each AP at each SI. When the condition in Line 2 of Algorithm 1 is true, different criteria can be used to find the MS that should be first handed off from AP i. In Algorithm 1, we choose the simplest distance-based criterion, so that the MS that has the maximum distance to the current AP is selected to handoff. The MS is denoted as m_i^*. AP i then notifies MS m_i^* to attempt to re-associate to another

AP. There can be other criteria when choosing which MS to handoff. For example, $m_i^* = \arg\min_{m \in \mathcal{M}_i} g_{im}$, in which case the MS with the worst link gain is selected, or $m_i^* = \arg\max_{m \in \mathcal{M}_i} E_{im}$, in which case the MS that consumes the most energy from AP i is selected. Both the link-gain based method and the energy based method may result in that the same MS is handed off between two APs back and forth more frequently, which is undesirable.

For each MS, after reporting the link gains to its currently associated AP at the beginning of the SI, it waits for a handoff notification from the AP while measuring its distances to nearby APs based on the received beacon signal strength from these APs. If a handoff notification is received, it sends a reassociation request to the nearest neighboring AP. An AP may receive handoff requests from multiple MSs. Upon receiving such requests, AP i accepts the requests, if no MSs currently associated to it should be handed off to other APs. AP i then solves problem P1 to find the power and time allocations for the new SI.

Algorithm 1 Realtime Energy Balancing Scheme (REB)

Reset $H_i = 0$.
if $\frac{E_i - \overline{E}_{\mathcal{N}_i}}{E_i} > \varepsilon$ **then**
    Set $H_i = 1$.
    Find $m_i^* = \arg\max_{m \in \mathcal{M}_i} d_{im}$.
    Update $\mathcal{M}_i = \mathcal{M}_i \setminus \{m_i^*\}$
    Find AP i^*, $i^* = \arg\min_{j \in \mathcal{N}_i} d_{jm_j^*}$.
end if
if Any MSs request to handoff into AP i **then**
    if $H_i = 0$ **then**
        Update $\mathcal{M}_i = \mathcal{M}_i \cup \{m_j^*\}$
    else
        No handoff requests are accepted.
    end if
end if
Find P_{im} and T_{im} by solving P1 using the updated $\mathcal{M}_i$

2.2.2 Longterm Energy Balancing Scheme (LEB)

Since the lifetime of the network depends on the long term energy consumption, it may not be necessary to balance the energy consumption of the APs in each SI. We define a weighted average of the energy consumption for AP i up to SI t as

$$\overline{E}_i(t) = \alpha\overline{E}_i(t-1) + (1-\alpha)E_i(t-1) \tag{2.18}$$

where $0 < \alpha < 1$. For a special case, $\overline{E}_i(0) = 0$. The value α is used to balance the effect of past and current energy consumption. When α is closer to 1, the definition gives a higher weight to the past; while when α is closer to 0, it gives a higher weight to the most recent SI. The value of $\overline{E}_i(t)$ is calculated at the end of each SI and exchanged between neighboring APs at the beginning of the following SI. By replacing all E_i's with the weighted average energy consumption of AP i, Algorithm 1 can be modified to balance the long term energy consumption of the APs. The value of α determines over what time scale the balanced energy consumption can be achieved among the APs. When α is equal to 0, LEB is equivalent to RET. When α is closer to 1, the energy balancing is achieved over a longer time period.

2.3 Numerical Results

We consider a one-dimensional network, where five APs, AP1 to AP5, are set along a road with equal distance d. In order to remove the boundary effect, we assume the distance between AP1 and AP5 is also equal to d. The APs are connected with wired Ethernet cables so that information exchanges between them take little overhead and can be neglected. Each MS, when its distance to AP 3 is less than 250m, moves at

Table 2.1: Default simulation parameters

Parameter	**Value**
Bandwidth ω	10 MHz
Required throughput η^*	42 Kbps
Noise power P_{noise}	-80 dBm
SI duration	100 ms
$T_{\max,i}$	36 ms
ε	0.6
Number of MSs	28
Distance between neighboring APs d	500 m
Initial energy available at each AP	500 J

a speed that is uniformly distributed between 20 km/h and 40 km/h. In other area, the speed of an MS is uniformly distributed between 20 km/h and 150 km/h [25]. The probability of moving in one of the two directions is 50%. Default parameters are listed in Table 2.1. For LEB, $\alpha = 0.3$, 0.5 and 0.7 are selected. The same initial energy is available at all APs, and the lifetime of the network is determined by the AP with the maximum energy consumption. In addition to network lifetime, we also collect results for average AP energy consumption and number of handoffs within a given time period T_s. The average AP energy consumption is the total amount of energy consumption of all APs from time zero to time T_s divided by the total number of the APs. The value of T_s is set to be much longer than the time period required for the LEB scheme to achieve balanced energy consumption.

In Figs. 2.1-2.3 we show the performance of REB and LEB schemes with different ε values. Fig. 2.1 shows that the average energy consumption increases significantly for both the schemes when ε is larger than 0.7. Between 0 and 0.6, having a larger ε can slightly reduce the average energy consumption. Overall, the average AP energy consumption is the lowest when ε is around 0.5-0.6. When ε is between 0 and 0.7,

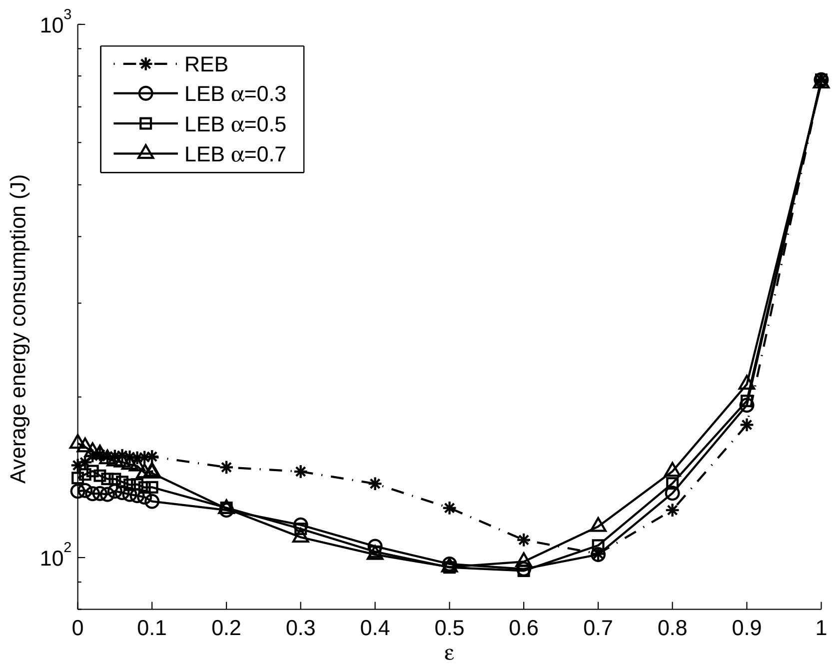


Figure 2.1: Average energy consumption

using LEB can result in lower average AP energy consumption than using REB. This proves the benefit for performing the long-term based method.

Fig. 2.2 shows that the lifetime of the network is the highest when ε is around 0.5-0.6, and using LEB results in longer network lifetime than using REB. By comparing Figs. 2.1 and 2.2 we can find that the two sets of the curves are consistent in the sense that when the average energy consumption is minimized, the network lifetime is maximized. This indicates that the energy consumption is well balanced among the APs.

Fig. 2.3 shows the total number of handoffs for all MSs during the simulated time interval of 700 seconds. It can be seen that using LEB results in a significantly smaller number of handoffs than using REB. The difference is especially big when ε is around

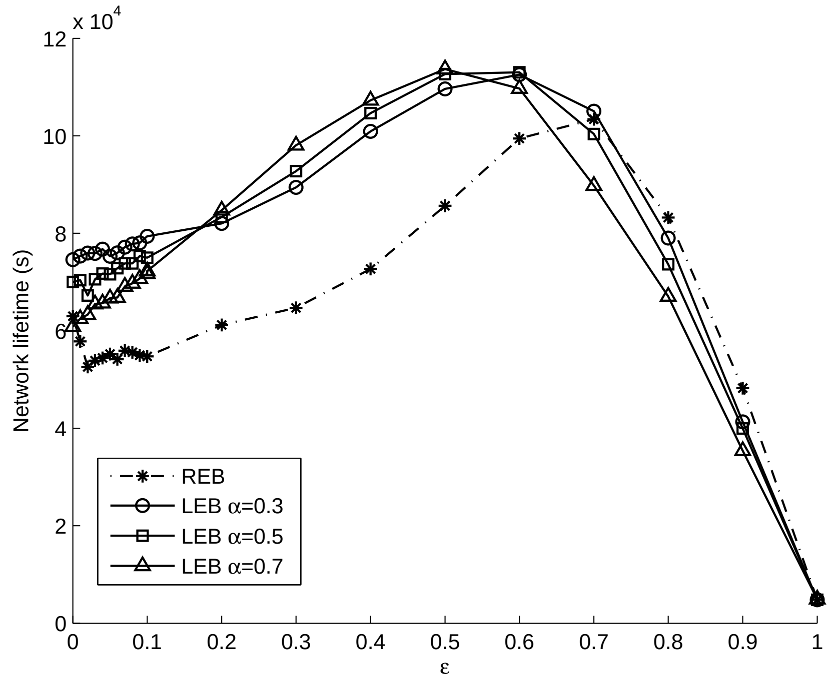


Figure 2.2: Network lifetime with 28 MSs

0.5. When ε is smaller, the handoff condition can be satisfied easily, and the number of handoffs is the largest when $\varepsilon = 0$. For LEB, the number of handoffs decreases significantly with ε. For REB, the number does not decrease very fast until ε is larger than 0.4. When ε is closer to 1, the number of handoffs is not affected much by ε for both schemes because it is difficult to satisfy the handoff condition.

Next, we demonstrate the performance of the REB and LEB schemes by varying the number of MSs. Figs. 2.4-2.6 show the performance. For comparison, we also simulate performance of the traditional distance-based handoff scheme, based on which an MS always associates to the closest AP. The transmission power and time allocations using the distance-based scheme are also solved from problem P1. This scheme is indicated by "Dist.-based" in the figures. The average AP energy consumption

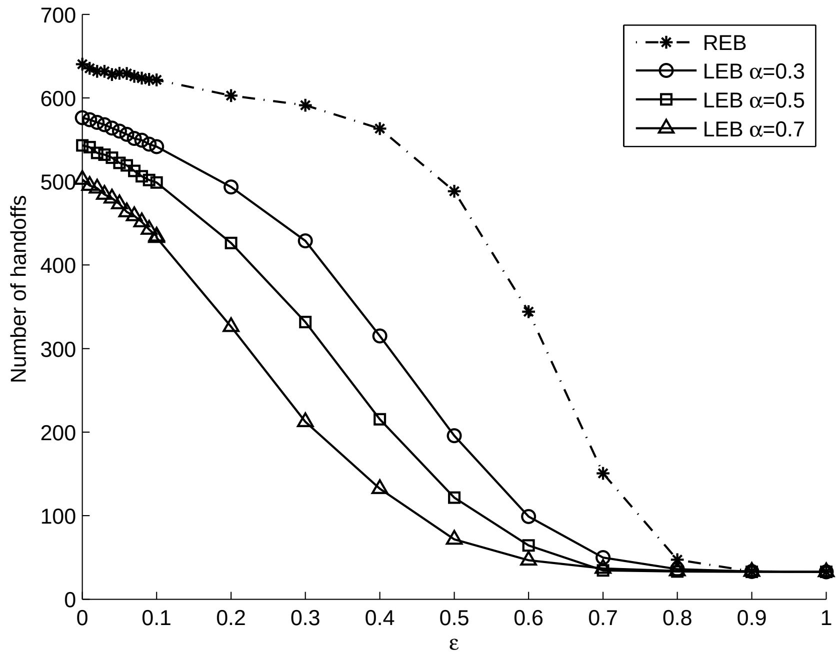


Figure 2.3: Number of handoffs

using the distance-based scheme is much higher than that using either of the proposed handoff schemes, and the network lifetime using the distance-based handoff is much shorter than using the proposed schemes. We further notice that in addition to the big difference in the average AP energy consumption between the proposed schemes and the distance-based handoff scheme, there is significant difference in the network lifetime between them. This is because the distance-based scheme leads to a phenomenon that one AP (most likely, this is AP 3 in the simulated system) may consume much more energy than the others, and this greatly shortens the network lifetime.

Fig 2.6 shows that both the REB and LEB schemes result in more handoffs than

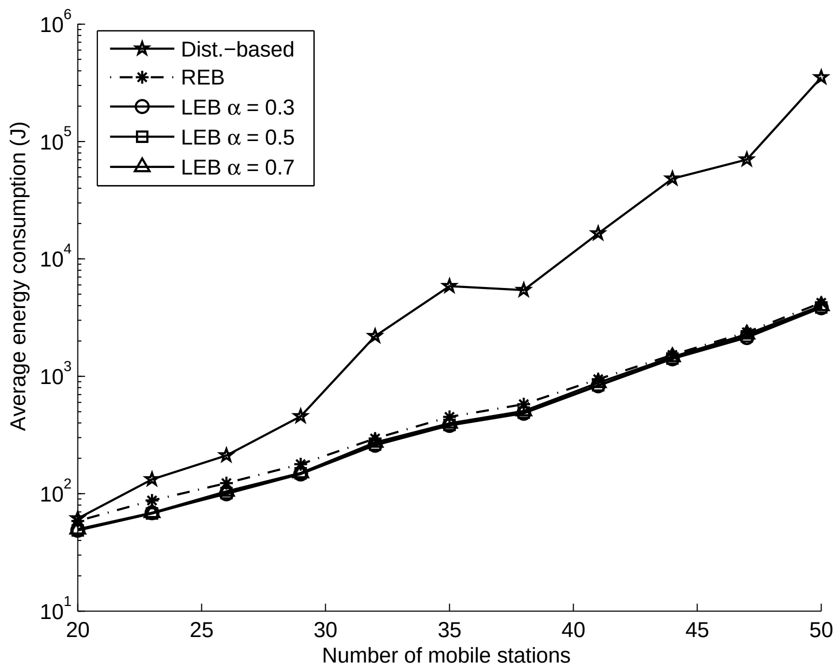


Figure 2.4: Average energy consumption

the distance-based scheme. Because of the need for balancing the AP energy consumption, some MSs may have to be handed off several times when they travel between two APs. Using the REB scheme results in the largest number of handoffs because it tries to balance the AP energy consumption in every SI. When using the LEB scheme, a smaller value of α forces the energy balancing to be achieved over a shorter period of time, and therefore leads to a larger number of handoffs. When $\alpha = 0.7$, the number of handoffs using the LEB scheme is approximately the same as that using the distance-based scheme. The benefit of using the LEB scheme is achieved under the condition that the available energy of the APs is sufficiently high so that it is not used up within a small number of SIs. If the initial energy of the APs is low, either REB or LEB with smaller α should be used.

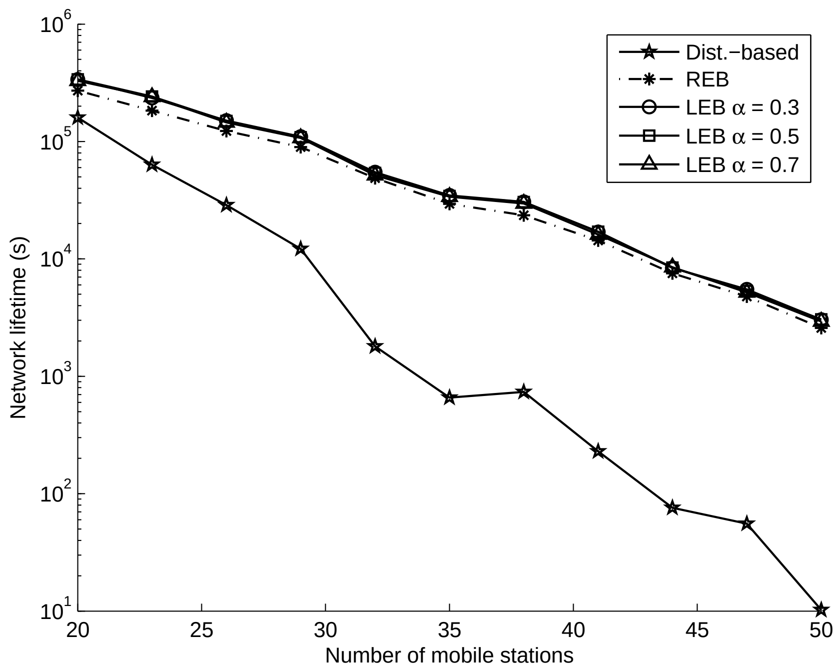


Figure 2.5: Network lifetime

2.4 Summary

In this chapter we have studied the MS handoff and AP resource allocation jointly in order to balance the energy consumption of battery-powered APs. Transmission power and time of the APs are solved based on the current associated MSs. Two handoff schemes have been proposed. Our results indicate that the network lifetime can be significantly extended using the proposed handoff schemes, compared to the distance-based handoffs, and using LEB can achieve balanced AP energy consumption with a smaller number of handoffs.

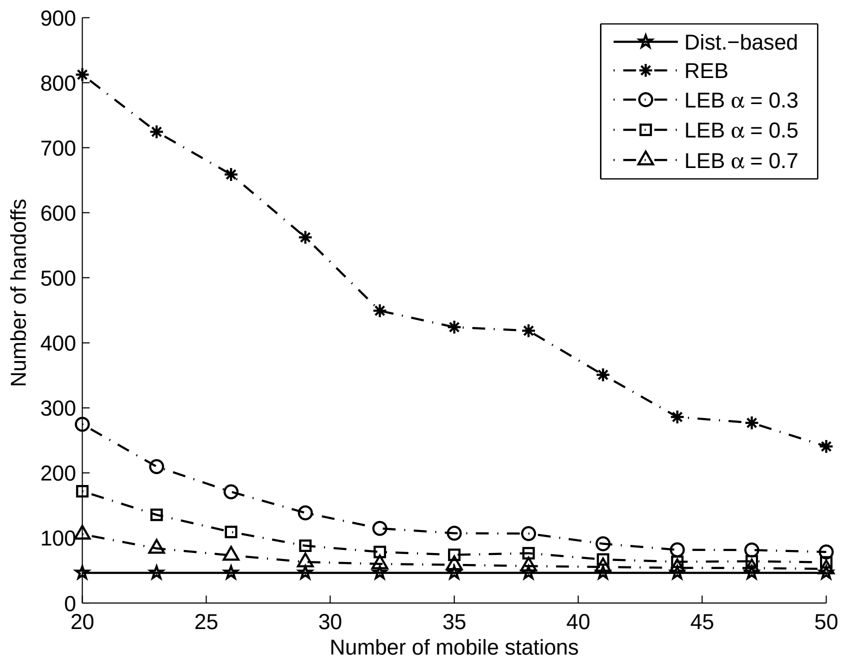


Figure 2.6: Number of handoffs

Chapter 3

Joint Handoff and Resource Management for Throughput Fairness

In this chapter we study the handoff and resource management problem jointly with transmission scheduling in order to provide fair throughput to the MSs. Within each AP's coverage area, the number of associated MSs and their channel conditions to the AP determine the transmission throughput that each MS can receive. MSs located in a heavily loaded AP receive lower throughput, compared to those located in a lightly loaded AP. Typical scenarios for such throughput unfairness can be found in a system where the MSs are not uniformly distributed in the network coverage area, or when the MSs have group mobility. When power control can be performed at the AP, the coverage area or transmission distance of the AP can be dynamically adjusted by changing the transmission power. With this, the traffic loads among different APs can possibly be balanced, and the MSs served by different APs may receive fair throughput. This is the basic idea and motivation for the work presented in this chapter.

The main challenge for implementing this is that a global optimum solution is difficult to achieve, since there is no central station for collecting all the necessary information in order to optimize the MS handoffs and the AP resource allocations in the whole network. In this chapter, we propose heuristic schemes that jointly consider the MS handoff and throughput fairness and examine their performance in different mobility scenarios. The remainder of this chapter is organized as follows. In Section 3.1, the problem of joint handoff and fair scheduling is formulated after introducing some background knowledge about the long-term proportional fairness. In Section 3.2 we describe the proposed handoff and resource allocation schemes. Handoff decisions are made at the beginning of each scheduling interval based on the information in the previous scheduling interval. Based on the handoff decisions, each AP then solves an optimization problem based on the local information in order to find the transmission time and power allocated to each associated MS. Numerical results are demonstrated in Section 3.3, followed by a summary in Section 3.4.

3.1 Problem Formulation

We consider a WMN similar to that described in Chapter 2. MSs communicate directly with their associated APs. Handoff of the MSs between different APs can only be performed at the beginning of a SI, and the association relations between the MSs and the APs are kept unchanged during each SI. Unlike in Chapter 2, there is no minimum throughput requirement for each MS. Our main concern is to provide fair throughput, as high as possible, among the MSs, while they are moving around in the network.

In general, consider a network where M links share the transmission medium. The throughput of link m at time t is denoted as $\eta_m(t)$, and $\overline{\eta}_m$ is the long term average throughput of link i. At each time t, $\overline{X}_m(t)$ is used to represent a weighted average rate for link m up to time t and is given by

$$\overline{X}_m(t) = (1-\gamma)\overline{X}_m(t-1) + \gamma\eta_m(t-1), \tag{3.1}$$

where $0 \leq \gamma \leq 1$ is a parameter that balances the weights of the throughput in the past and the most recent SIs. When γ is closer to 1, more weight is given to the current throughput. When $\gamma = 1$, the weighted average throughput is equal to the throughput in the current SI. For a special case, $\overline{X}_m(0) = 0$. A general scheduling problem based on the long term average throughput to the MSs can be formulated to maximize a concave objective function $U(\overline{\mathbf{X}})$, where $\overline{\mathbf{X}} = [\overline{X}_1(t), \overline{X}_2(t), \ldots, \overline{X}_M(t)]$. When $U(\overline{\mathbf{X}}) = \sum_{m=1}^{M} \log \overline{\eta}_m$, proportional fairness (PF) is achieved for the average throughput among the links. PF is proved to be the best tradeoff between effective resource utilization and user satisfaction. It is proved in [26] that this objective can be achieved iteratively through SI-by-SI scheduling. Given the system utility at time t, $U(\overline{\mathbf{X}}(t))$, it is proved that the objective of maximizing the utility function $U(\overline{\mathbf{X}})$ is to find the optimum throughput for each MS in the next SI so that to maximize $U(\overline{\mathbf{X}}(t+1)) - U(\overline{\mathbf{X}}(t))$, and this is equivalent to finding a throughput vector $[\eta_m(t), m = 1, 2, \ldots, M]$ so that to maximize

$$\sum_{m=1}^{M} \frac{\eta_m(t)}{\overline{X}_m(t)}. \tag{3.2}$$

At each time t, in order to maximize the objective in (3.2), the MSs with either higher $\eta_m(t)$ or lower $\overline{X}_m(t)$ are given a higher priority to transmit.

Back to the WMN that we consider, let $P_{im}(t)$ and $T_{im}(t)$, respectively, represent the amount of transmission power and time that AP i transmits to MS m during SI t, $R_{im}(t)$ represent the instantaneous transmission rate of AP i to MS m, and $\mathcal{M}_i(t)$ be a set of the MSs associated to AP i at SI t. Furthermore, we define a set of binary variables $A_{im} \in \{0, 1\}$ to represent the association relationship between the MSs and the APs. When MS m is associated to AP i, $A_{im} = 1$; otherwise, $A_{im} = 0$. We then define several matrices, $\mathbf{A}(t) = [A_{im}(t)]$, $\mathbf{P}(t) = [P_{im}(t)]$, and $\mathbf{T}(t) = [T_{im}(t)]$ for all i and m. In addition, we define a vector $\eta(\mathbf{t}) = [\eta_m(t)]$. The handoff and long term throughput PF problem can be formulated as

$$\text{P3.} \quad \max_{\eta(\mathbf{t}),\mathbf{P}(t),\mathbf{T}(t),\mathbf{A}(t)} \sum_{m=1}^{M} \frac{\eta_m(t)}{\overline{X}_m(t)} \tag{3.3}$$

$$\text{s.t.} \quad \overline{X}_m(t) = (1-\gamma)\overline{X}_m(t-1) + \gamma\eta_m(t-1), m = 1, 2, \ldots, M \tag{3.4}$$

$$\eta_m(t) = \sum_{\text{all } i} R_{im}(t)T_{im}(t), m = 1, 2, \ldots, M \tag{3.5}$$

$$R_{im}(t) = A_{im}\omega \log_2 \left[1 + \frac{P_{im}(t)g_{im}(t)}{P_{noise}}\right], m \in \mathcal{M}_i(t) \tag{3.6}$$

$$\sum_{\text{all } i} A_{im} \leq 1, m = 1, 2, \ldots, M \tag{3.7}$$

$$\sum_{m=1}^{M} T_{im}(t) \leq T_{\max,i}, \text{all } i \tag{3.8}$$

$$0 \leq P_{im}(t) \leq P_{\max,i}, m = 1, 2, \ldots, M \tag{3.9}$$

$$A_{im} \in \{0, 1\}, \text{ for all } m \text{ and } i \tag{3.10}$$

If the solution can be found for the above optimization problem, the PF is achieved for the average throughput among all the MSs when t is sufficiently large. On the other hand, solving this problem is unlikely because the MSs are served by different APs, and there is no central station available to collect all required information and run the global optimization problem. Therefore, practical schemes are needed to achieve this objective.

3.2 Proposed Schemes

The basic idea of the proposed schemes is to separate the handoff decisions from the AP resource allocations. The handoff decisions are based on limited information exchanged between neighboring APs. Given the associations of the MSs, we have $\mathcal{M}_i(t) = \{m|1 \leq m \leq M, A_{im}(t) = 1\}$. Each AP then performs the following optimization problem locally to find the resources allocated to the associated MSs.

$$\text{P4.} \quad \max_{\eta_{\mathbf{i}}(\mathbf{t}),\mathbf{P_i}(\mathbf{t}),\mathbf{T_i}(\mathbf{t})} \sum_{m\in\mathcal{M}_i(t)} \frac{\eta_m(t)}{\overline{X}_m(t)} \tag{3.11}$$

$$\text{s.t.} \quad \overline{X}_m(t) = (1-\gamma)\overline{X}_m(t-1) + \gamma\eta_m(t-1), m \in \mathcal{M}_i(t) \tag{3.12}$$

$$\eta_m(t) = R_{im}(t)T_{im}(t), m \in \mathcal{M}_i(t) \tag{3.13}$$

$$R_{im}(t) = \omega \log_2\left[1 + \frac{P_{im}(t)g_{im}(t)}{P_{noise}}\right], m \in \mathcal{M}_i(t) \tag{3.14}$$

$$\sum_{m\in\mathcal{M}_i(t)} T_{im}(t) \leq T_{\max,i} \tag{3.15}$$

$$P_{im}(t) \leq P_{\max,i}, m \in \mathcal{M}_i(t) \tag{3.16}$$

By solving this problem, PF is achieved for the throughput among the MSs associated to the same AP. We then design two handoff schemes, utility-based and number-based schemes, so that the PF is achieved among the MSs in the entire network.

We first describe the utility-based handoff scheme. Consider each term in the summation of the objective function in (3.11) as the utility that an individual MS can contribute. Then the average utility for all the MSs associated to AP i can be defined as

$$\overline{\mathcal{U}}_i = \frac{\sum_{m \in \mathcal{M}_i} \frac{\eta_{im}(t)}{\overline{X}_m(t)}}{|\mathcal{M}_i|}. \tag{3.17}$$

At the end of each SI, neighboring APs exchange the value of $\overline{\mathcal{U}}_i$. After this, AP i calculates the average of the $\overline{\mathcal{U}}_j$ values for $j \in \mathcal{N}_i$ as:

$$\mathcal{U}_{av,i} = \frac{\sum_{j \in \mathcal{N}_i} \overline{\mathcal{U}}_j}{|\mathcal{N}_i|}. \tag{3.18}$$

If $\frac{\overline{\mathcal{U}}_i - \mathcal{U}_{av,i}}{\overline{\mathcal{U}}_i} < \rho$, an indicator H_i is set to 1, and some MSs currently associated to AP i should be handed off to the neighboring APs, where $0 < \rho \ll 1$. In Algorithm 2, the first part is for the case when AP i has lower average per-MS utility than the average value of its neighbors, and the second part is for the case when the AP has higher average per-MS utility than the average value of its neighbors.

Algorithm 2 Utility-based Scheme

Reset $H_i = 0$.
if $\frac{\overline{\mathcal{U}}_i - \mathcal{U}_{av,i}}{\overline{\mathcal{U}}_i} < \rho$ **then**
    Set $H_i = 1$.
    Find $m_i^* = \arg\max_{m \in \mathcal{M}_i} d_{im}$.
    Find AP i^*, $i^* = \arg\min_{j \in \mathcal{N}_i} d_{jm_j^*}$.
    if The handoff request is accepted by AP i^* **then**
        Update $\mathcal{M}_i = \mathcal{M}_i \setminus \{m_i^*\}$
    end if
end if
while There is at least one MS still requesting to handoff into AP i **do**
    if $H_i = 0$ **then**
        Accept the first pending request and update $\mathcal{M}_i$.
    end if
end while
Find η_{im}, P_{im} and T_{im} by solving P4 using the updated $\mathcal{M}_i$

Given ρ, the number of MSs that should be handed off and which APs these MSs may be handed off to depend on specific conditions. In order to limit the implementation complexity, we consider that at most one MS can be handed off from each AP at each SI. When the condition in Line 2 is true, different criteria can be used to find the MS that should be handed off from AP i. In Algorithm 2, we choose the simplest distance-based criterion, so that the MS that has the maximum distance to the current AP is selected to handoff. The MS is denoted as m_i^*. AP i then notifies MS m_i^* to attempt to re-associate to another AP.

For each MS, after reporting the link gains to its currently associated AP at the beginning of the SI, it waits for a handoff notification from the AP while measuring its distances to nearby APs based on the received beacon signal strength from these APs. If a handoff notification is received, it sends a reassociation request to the nearest neighboring AP. An AP may receive handoff requests from multiple MSs. Upon receiving such requests, AP i accepts the requests, if no MSs currently associated to it should be handed off to other APs. AP i then solves problem P4 to find power and time allocations for the new SI.

Instead of making the handoff decisions based on the utility function, the second handoff criterion simply makes use of the number of MSs associated to each AP. Algorithm 3 outlines the number-based handoff scheme performed at AP i at the beginning of each SI, where the time variables are omitted for simple notation. Denote $|\mathcal{M}_i|$ the number of MSs associated to AP i. At the end of each SI, neighboring APs exchange the values of $|\mathcal{M}_i|$. Upon receiving $\mathcal{M}_j$'s from AP j for all $j \in \mathcal{N}_i$, AP i

calculates the average number of MSs served by the neighboring APs as

$$\overline{|\mathcal{M}|}_i = \frac{\sum_{j \in \mathcal{N}_i} |\mathcal{M}_j|}{|\mathcal{N}_i|}. \tag{3.19}$$

If $|\mathcal{M}_i|$ is larger than $\overline{|\mathcal{M}|}_i$ by a small number ε, an indicator H_i is set to 1, and some MSs currently associated to AP i should be handed off to the neighboring APs. In Algorithm 3, the first part is for the case where the AP has more associated MSs than the average number of its neighbors, and the second part is for the case when the AP has fewer associated MSs than the average number of its neighbors. This handoff scheme works very similarly to the utility-based one. The main difference is that in the number-based scheme it is easy to set a criterion as to whether an AP can accept more handoff requests after it has already accepted one or more handoff requests. In Algorithm 3, the AP does not accept more handoff requests if the condition defined in Line 13 is true. On the other hand, a similar criterion is difficult to specify in the utility-based scheme without recalculating the AP resource allocations and exchanging the corresponding information between neighboring APs after each handoff.

3.3 Numerical Results

We consider a one-dimensional network, where five APs, AP1 to AP 5, are set along a road. All the neighboring APs are separated with equal distance d. AP1 and AP 5 are at the edge. In order to remove the boundary effect, we assume that the distance between these two APs is also d. A number of MSs move along the road. Their moving speed is uniformly distributed between zero and a maximum speed. Each

Algorithm 3 Number-based Scheme

Reset $H_i = 0$.
if $|\mathcal{M}_i| - \overline{|\mathcal{M}|}_i > \varepsilon$ **then**
  Set $H_i = 1$.
  Find $m_i^* = \arg\max_{m \in \mathcal{M}_i} d_{im}$.
  Find AP i^*, $i^* = \arg\min_{j \in \mathcal{N}_i} d_{jm_j^*}$.
  if MS m_i^* can be handed off to AP i^* **then**
    Update $\mathcal{M}_i = \mathcal{M}_i \setminus \{m_i^*\}$
  end if
end if
while $H_i = 0$ and there is at least one MS still requesting to handoff into AP i **do**
  Accept the first pending request.
  Update $\mathcal{M}_i = \mathcal{M}_i \cup_{j \in \mathcal{N}_i} m_j^*$
  if $\mathcal{M}_i < \overline{|\mathcal{M}|}_i + \varepsilon$ **then**
    $H_i = 1$
  end if
end while
Find η_{im}, P_{im} and T_{im} by solving P4 using the updated $\mathcal{M}_i$

MS can move in either direction along the road with equal probability. In order to create a situation of unbalanced traffic load, we introduce Group Mobility(GM) in the simulation. When a certain number of MSs are in GM, different from other MSs, they always move as a group with the same direction and speed. All the MSs in GM are located very close to each other at the beginning of the simulation and their relative locations are unchanged throughout the simulation. Default parameters are listed in Table 3.1.

For comparison, we also consider two other handoff criteria, one is based on throughput, and the other one is based on distance. The throughput-based scheme uses the same handoff criterion as the number-based one, except that when the AP allocates its transmission power and time, the objective function is changed to $\max_{\eta(\mathbf{t}),\mathbf{P}(\mathbf{t}),\mathbf{T}(\mathbf{t})} \sum_{m \in \mathcal{M}_i} \eta_{im}(t)$. That is, the objective of the resource allocations

Table 3.1: Default simulation parameters

Parameter	**Value**
Bandwidth ω	10 MHz
Noise power P_{noise}	-90 dBm
SI duration	100 ms
$T_{\max,i}$	36 ms
ε	1
ρ	0.05
$P_{\max}$	0.005 w
Number of MSs	30 - 60
MS maximum moving speed	10 m/s
Distance between neighboring APs d	1000 m

within each AP is to maximize the total throughput to all the associated MSs. For the distance-based scheme, each AP solves the optimization problem P4 for allocating resources to its associated MSs, each of which always associates to the closest AP at the beginning of each SI. We consider different mobility scenarios and demonstrate the numerical results below in terms of both throughput fairness and the average throughput. We use the Jain's fairness index [27] for evaluating the throughput fairness, and the average throughput is the total throughput accumulated over the simulation time period divided by the number of MSs and then averaged over the entire simulated time interval.

3.3.1 Performance vs. number of MSs

In this set of simulations, we consider three different group mobility scenarios, where 10%, 50%, and 90% MSs move in a group, respectively, and the rest of the MSs move independently of each other. We vary the total number of MSs from 30 to 60 in each of these scenarios, and the simulation results are shown in Figs. 3.1, 3.2 and 3.3. We can see from part (a) of all the three figures that the utility-based and number-based schemes both achieve very high fairness index — close to 1. Although the distance-based and the throughput-based schemes can all achieve good fairness when a small percent of the MSs are in GM, the fairness index using these two schemes is reduced greatly as more MSs are in GM. The reason for this is that the utility-based and number-based schemes consider both load balancing and throughput fairness, and therefore, result in good fairness even when a large number of MSs move in a group, which normally can result in significant load unbalancing. While the throughput-based scheme also balances the traffic loads among neighboring APs, the individual APs do not provide fair resource allocations among their own associated MSs. For the distance-based scheme, traffic loads of different APs can be significantly different when the MSs have high group mobility. It is also interesting to see that there is no significant difference between the number-based and the utility-based schemes in terms of fairness in different group mobility scenarios. This indicates that both schemes can effectively balance the traffic load among the APs. Although balancing the number of MSs associated to the APs is not exactly equivalent to balancing the traffic loads among the APs, the number-based scheme can easily limit the maximum number of MSs handed off to an AP. For the utility-based method, this is difficult as mentioned before.

Part (b) of the three figures shows the average throughput performance. In all the three group mobility scenarios, the throughput-based scheme always achieves the highest throughput, while the number-based and utility-based schemes achieve lower throughput than the other two schemes. This is the tradeoff between resource utilization and fairness. The number-based and utility-based schemes sacrifice the resource utilization in order to achieve high fairness. For all the schemes, the average throughput decreases as more MSs join in the group mobility.

3.3.2 Performance vs. moving speed

Figs. 3.4, 3.5, and 3.6 show the performance of the network when varying the MS moving speed. We simulated 36 MSs in three different group mobility scenarios. Part (a) of the figures shows the fairness index. When only a small percentage of the MSs is in group mobility, all the four schemes achieve high fairness index. As the size of group mobility increases, the fairness index of both the throughput-based and distance-based schemes decreases significantly. This has been explained before. It can be seen that in most cases the moving speed has little effect on the fairness. Further results (not shown) indicate that the moving speed mainly affects the time scale over which the fairness is achieved. When the moving speed is low and more MSs move in a group, it takes a longer time to achieve fairness. In terms of the total throughput, we have similar observation as before. That is, the throughput-based scheme achieves the highest throughput. The utility-based and number-based schemes achieve approximately the same throughput, although the throughput using the number-based scheme is slightly higher. Similar to the fairness performance, moving speed does not affect the average throughput performance very much.

3.3.3 Performance vs. group size

Fig. 3.7 shows the performance vs. the percentage of MSs that move in the same group, where the total number of MSs is 40. When the percentage is zero, all the MSs move independently of each other; and when it is one, all the 40 MSs move as one group. From part (a) we can see that the fairness index is not very much affected by the group size for both the utility-based and number-based schemes. While for the throughput-based scheme, the fairness index decreases dramatically as the group size increases. For the distance-based scheme, the fairness index decreases with the group size. On the other hand, when all the MSs are in the same moving group, they all served by the same AP, and the throughput fairness is back to 1.

When the group size is relatively small, the throughput-based scheme achieves the highest throughput, and both the throughput-based and the distance-based scheme achieve higher throughput than the utility-based and number-based schemes. When the group size is relatively large, the throughput of both the throughput-based and distance-based schemes decreases significantly. On the other hand, the throughput of the utility-based and number-based schemes is not much affected by the group size. This observation further indicates that the utility-based and the number-based schemes can effectively balance the traffic load among the APs.

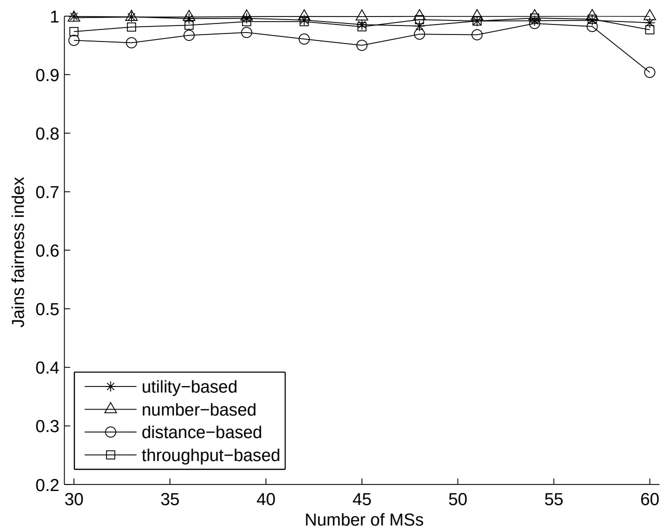
3.3.4 Performance vs. AP transmission distance

In this simulation, we limit the maximum transmission distance of the APs and examine the fairness and throughput performance. The maximum transmission distance is a pre-specified parameter. There are 36 MSs in the network and 32 of them move in a group. Fig. 3.8 shows the fairness and throughput performance. From this figure we can see that as the maximum allowed transmission distance increases, the fairness index of both the utility-based and number-based schemes increase significantly and then reaches 1. As this distance increases, more MSs have more than one choice when deciding which APs they can associate to, and having this freedom helps balance the traffic loads among the APs and achieve better throughput fairness to the

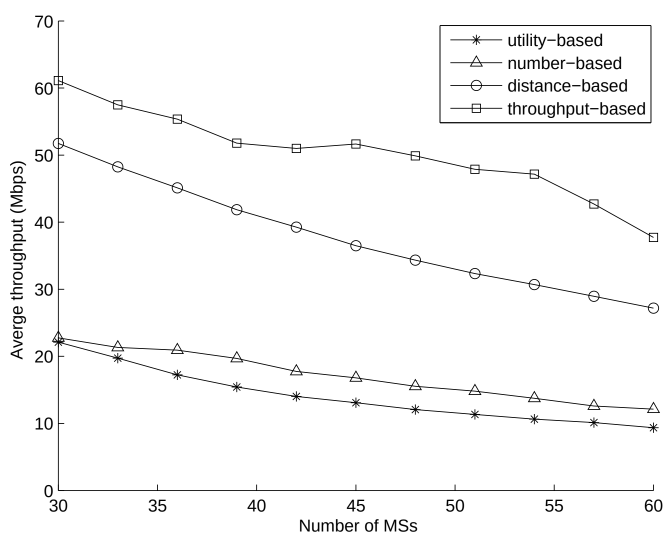
MSs. Meanwhile, we notice that the throughput performance decreases with the maximum AP transmission distance due to the tradeoff between the fairness and resource utilization. The distance-based scheme is not affected by the maximum transmission distance of the APs as long as the limited maximum AP transmission distance does not result in any coverage holes in the service area.

3.4 Summary

In summary, we have proposed two schemes that jointly consider MS handoff and AP resource allocation in order to achieve throughput fairness. Our results have demonstrated that the number-based scheme and the utility-based scheme are both good at achieving fair throughput among the MSs, and the schemes are not sensitive to MS moving speed or group mobility patterns. The number-based scheme is simpler than the utility-based one in term of implementation.

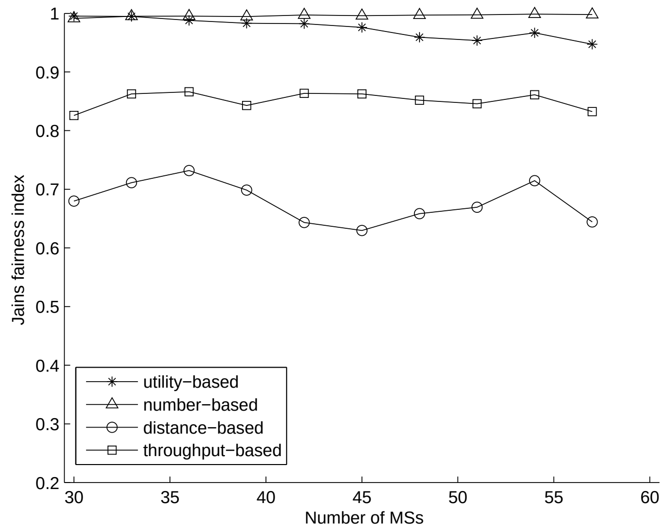


(a) fairness

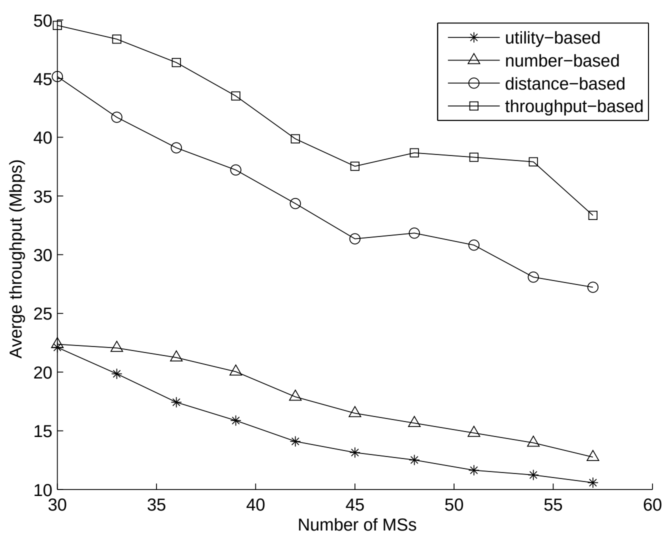


(b) average throughput

Figure 3.1: Performance vs. total number of MSs: 10% of MSs in group mobility

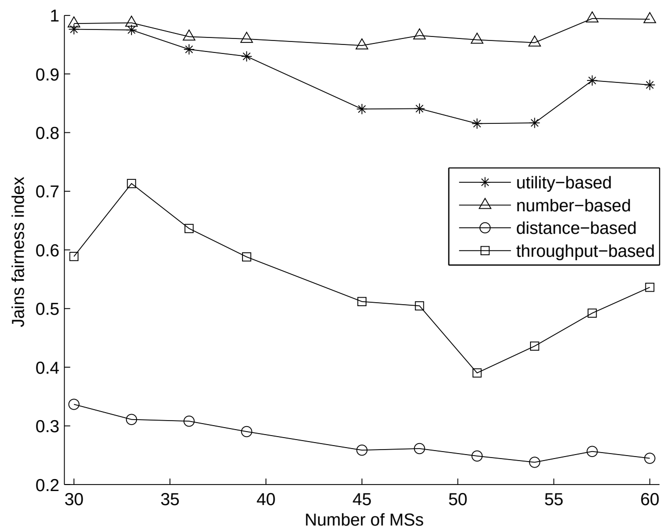


(a) fairness

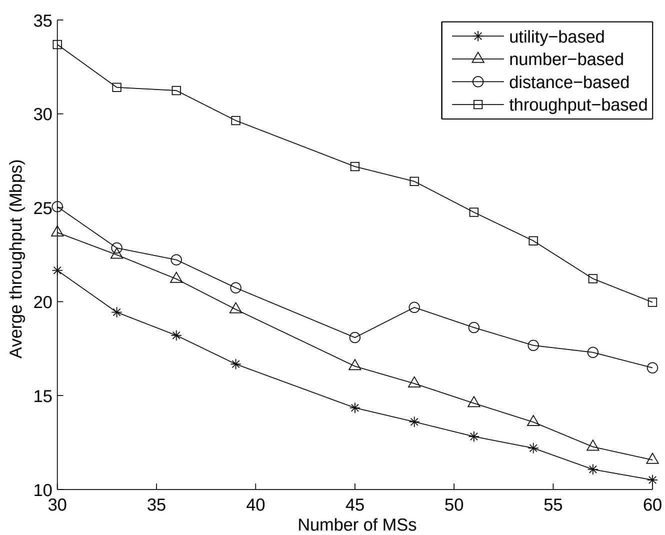


(b) average throughput

Figure 3.2: Performance vs. total number of MSs: 50% of MSs in group mobility

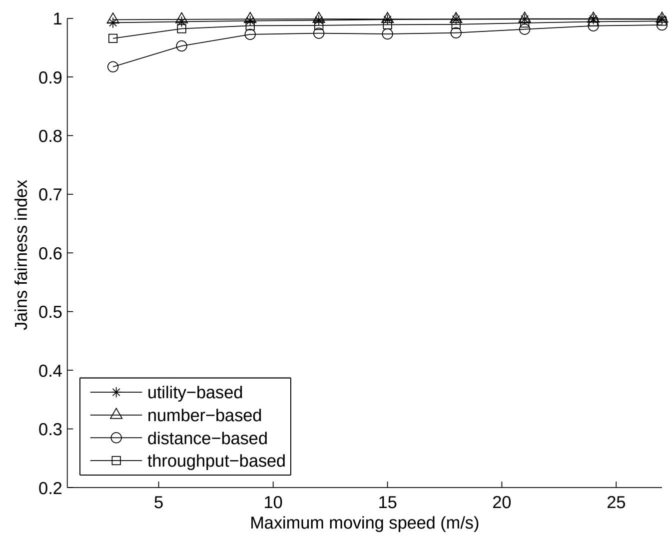


(a) fairness

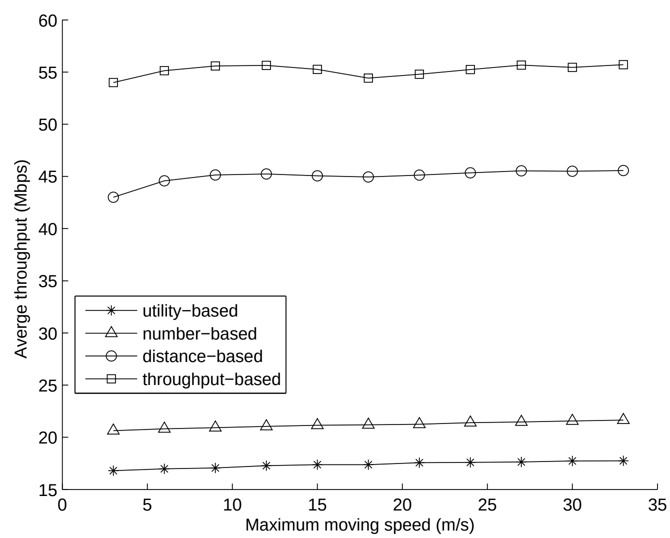


(b) average throughput

Figure 3.3: Performance vs. total number of MSs: 90% of MSs in group mobility

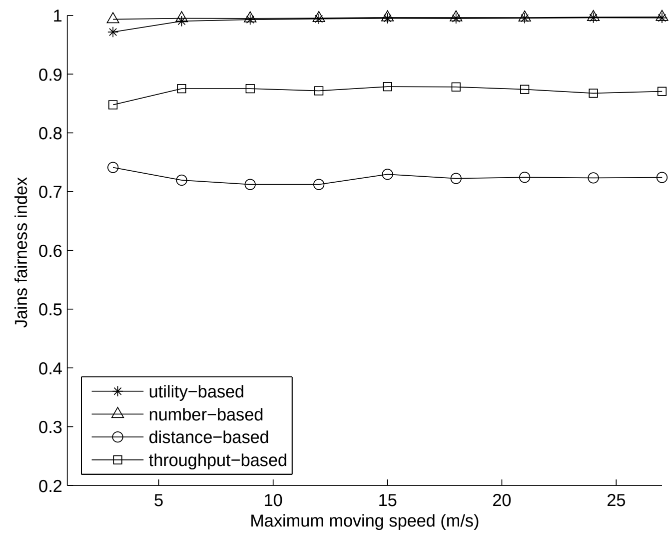


(a) fairness

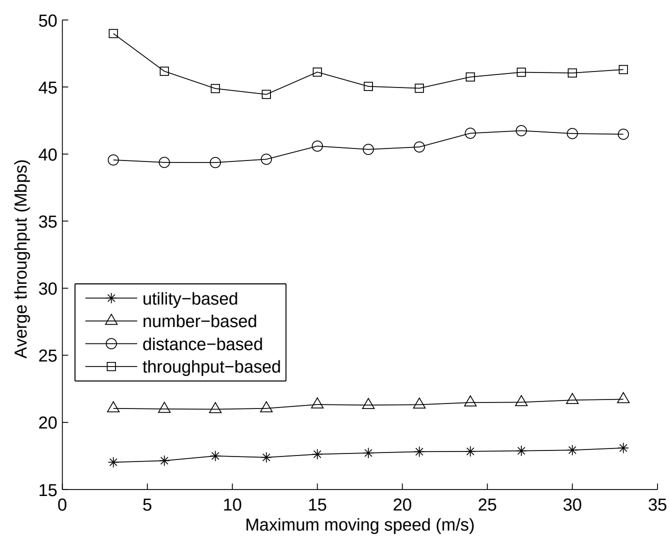


(b) average throughput

Figure 3.4: Performance vs. maximum moving speed: 10% of MSs in group mobility

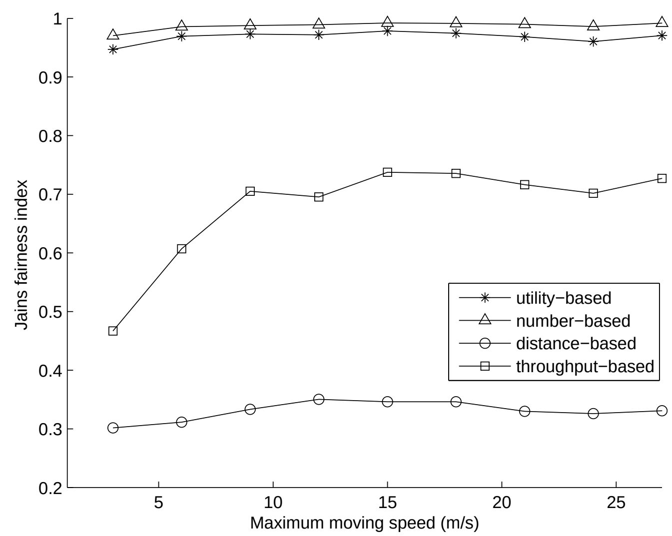


(a) fairness

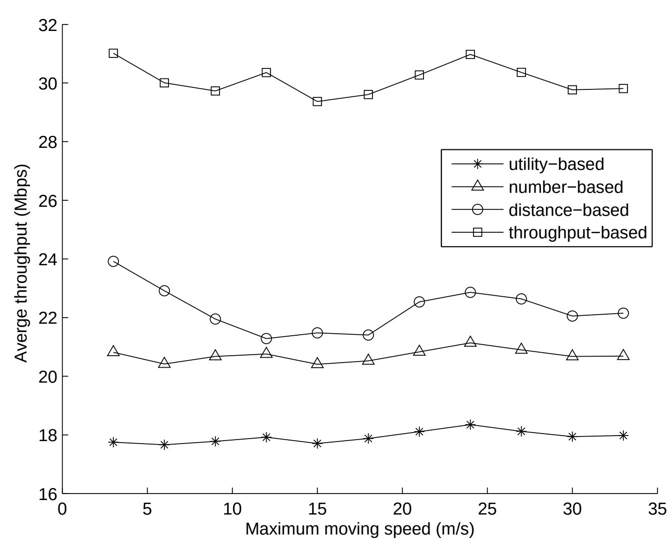


(b) average throughput

Figure 3.5: Performance vs. maximum moving speed: 50% of MSs in group mobility

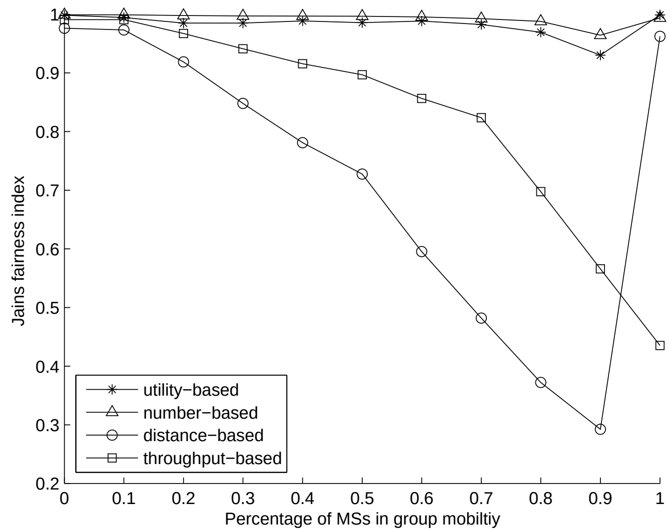


(a) fairness

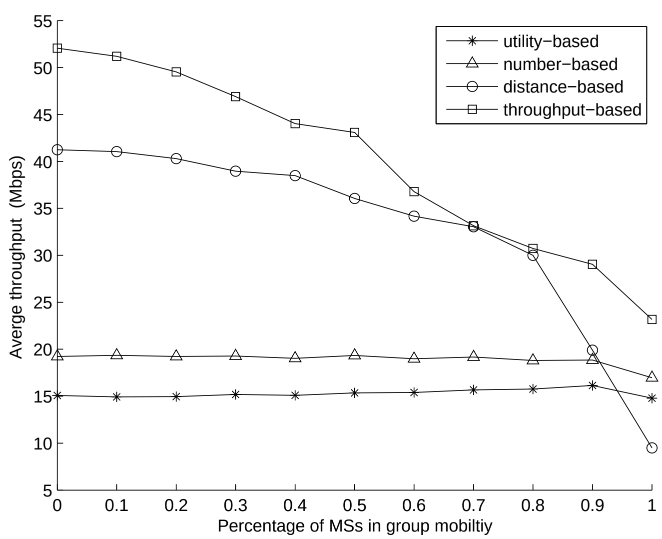


(b) average throughput

Figure 3.6: Performance vs. maximum moving speed: 90% of MSs in group mobility

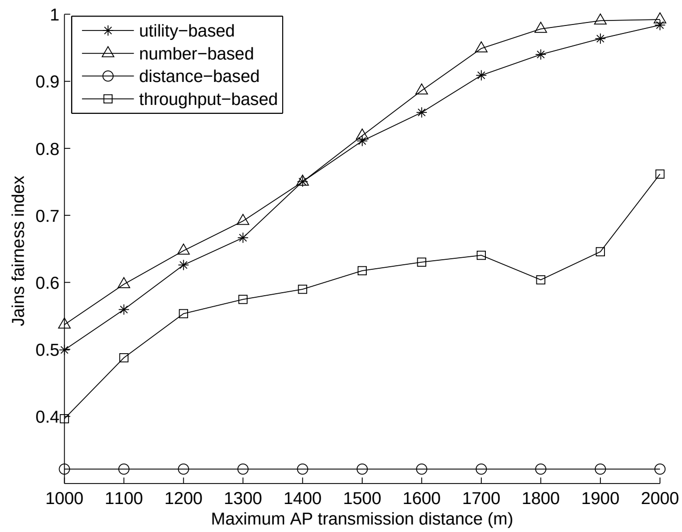


(a) fairness

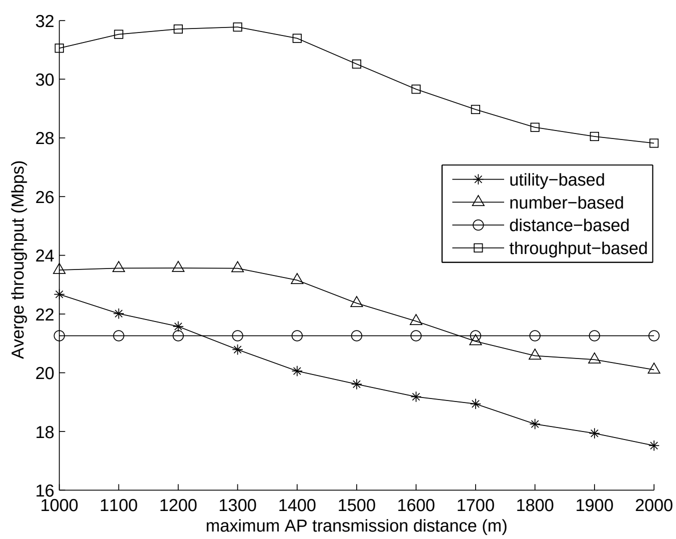


(b) average throughput

Figure 3.7: Performance vs. percentage of MSs in group mobility



(a) fairness



(b) average throughput

Figure 3.8: Performance vs. maximum AP transmission distance

Chapter 4

Conclusions and Future Works

In this thesis, we have studied handoff and resource management jointly for a WMN where APs dynamically adjust their transmission power, rate, and time to the MSs. The objectives are to balance the AP energy consumption and achieve fair throughput for the MSs. We have proposed two handoff and resource allocation schemes for balancing the AP energy consumption. Our results demonstrate that both the proposed schemes can effectively balance the energy consumption of different APs, and the LEB scheme achieves better performance, provided the initial energy at the APs is sufficient for the scheme to reach the long-term effect. We have also proposed two handoff and resource allocation schemes for achieving fair throughput to the MSs, and the numerical results demonstrate that they both achieve very high fairness index under different mobility patterns, and the number-based scheme provides slightly higher throughput performance and is easier to implement.

The research work in this thesis can be further extended in different directions.

- Solving the global optimum solution for problems P2 and P3 can provide the performance benchmarks for the proposed schemes in Chapters 2 and 3, respectively. We will find an efficient method to solve these problems.

- We have studied the handoff and resource management problem for balancing the AP energy consumption, and then for achieving fair throughput for the MSs. Next we will try to combine the AP energy consumption and fair throughput problems and study how handoff management and AP resource allocations can optimize both the objectives.

- Instead of using the Shannon-Hartley theorem for the relationship between the transmission rate and SNR, which gives the upper bound of the transmission rate for given SNR, we will look at more practical physical layer designs, based on which to find the relationship between the transmission rate and power. Adaptive modulation and coding can be used to improve the resource utilization.

- Because of the computation complexity, all the computer simulations are conducted with a small number of APs arranged in a one-dimensional network. We will further simulate the performance of the proposed schemes in two-dimensional networks.

- All the problem formulations in this thesis are done for the downlink transmissions. Next we will extend the work to the uplink transmissions. Although some formulations in this thesis also apply for the uplink, special characteristics of the access channel in the uplink can make the problems more challenging.

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