# Analyzing the Effect of Soft Handover on Handover Performance Evaluation Metrics Under Load Condition

**By**

**Nitish Kumar Panigrahy**

**Under the guidance**

**of**

**Dr. Sasthi Ch. Ghosh**

Submitted in Partial Fulfillment of the Requirements
for the Degree of Master Of Technology
in Computer Science
at Indian Statistical Institute, 2016

# Indian Statistical Institute

Department of Computer Science

Date: July 8, 2016

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

**Nitish Kumar Panigrahy**

ENTITLED

## Analyzing the Effect of Soft Handover on Handover Performance Evaluation Metrics Under Load Condition

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

**MASTER OF TECHNOLOGY IN COMPUTER SCIENCE**

---

**Thesis Advisor:**
**Dr. Sasthi Ch. Ghosh**

# Acknowledgments

This project would not have been possible without the support of many people. Firstly, I would like to express my sincere regards to my guide **Dr**. **Sasthi Ch**. **Ghosh** who have been the constant source of motivation for the successful completion of this work. I thank him for giving me the opportunity to work under him and helping me realize my full potential.

I thank my friends for their help and support. Last but not the least I thank my parents and family members for their constant support and motivation which helped me believe I can successfully complete this project.

# Analyzing the Effect of Soft Handover on Handover Performance Evaluation Metrics Under Load Condition [1]

Nitish Kumar Panigrahy

Department of Computer Science
Indian Statistical Institute
Kolkata, India
2016

## ABSTRACT

With increasing popularity of wireless local area network (WLAN) and emerging real time applications, seamless mobility has become one of the primary concerns. Hence the choice of a proper handover algorithm is of utmost importance. Various performance evaluation metrics for handover algorithms have been proposed in this regard. We argue that in a multiple AP scenario, the load on each of the APs, the requested data rate of the mobile terminal (MT) and the soft handover have significant impact on these metrics. In this thesis, an analytical framework has been proposed to measure various handover performance evaluation metrics under both load condition and soft handover for a specific data rate request. Our approach is based on finding the circular region centered around an AP within which the requested data rate can be satisfied. We have considered WLAN usage efficiency, handover failure probability and unnecessary handover probability as evaluation metrics. We have analyzed the impact of load and soft handover on these metrics. Moreover, the impact of velocity on these metrics has also been analyzed.

[1] A part of this thesis appeared in Proceedings of the 14th IEEE International Symposium on Network Computing and Applications (IEEE NCA 2015), Cambridge, MA, USA, September 28-30, 2015.

# Table of Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

Past few years have witnessed a significant growth in the mobile data traffic on a global scale. With ever increasing data request of mobile users various mobile applications, online streaming media and social networks are driving enormous traffic volumes throughout the globe. It has certainly become difficult to meet these traffic demands by the wide coverage infrastructure of cellular networks mainly because of its high cost and limited data rate. Hence with the provision of higher data rate at lower cost and the ease of installation, WLANs seem to be a better alternative over the cellular networks. In an infrastructure based WLAN, the service area is divided into a number of cells where each cell is controlled by an AP which coordinates all communications that take place in that cell. The MTs then access this network through these APs. Emerging real time applications have made it mandatory to support seamless and continuous internet connectivity within the WLAN coverage area. For an MT, the transition from one AP to other may involve heavy packet loss and outage degrading the quality of data transmission. Hence choosing an efficient handover algorithm has become one of the primary concerns.

## 1.1 Handover Overview

Handover is basically changing one access network to other while user is still in motion maintaining the desired data access. Depending on the access network that each point

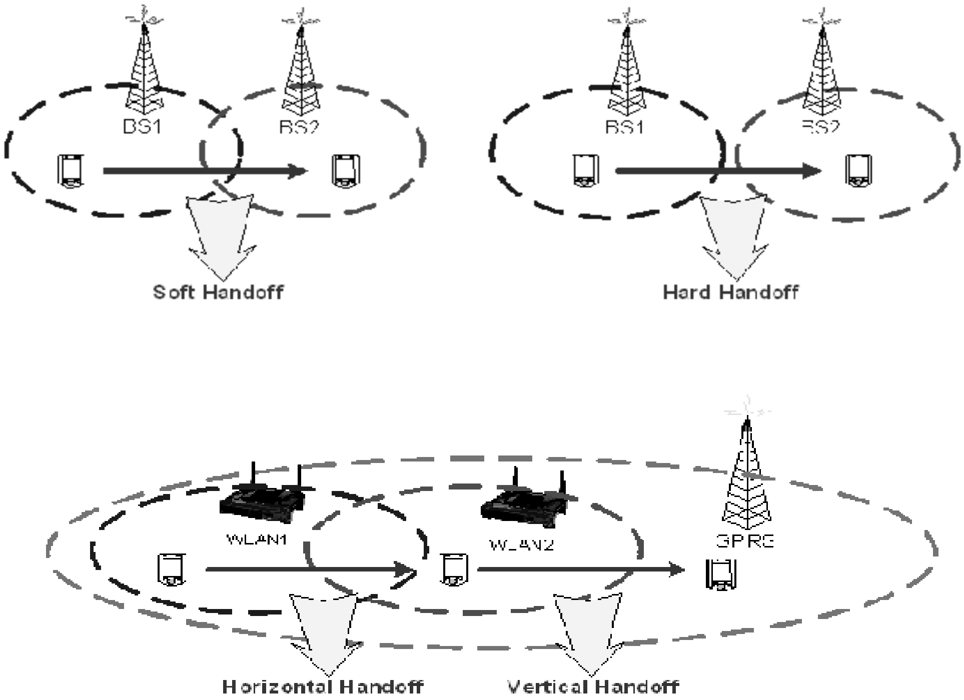


Fig. 1.1: Handover Classification [30]

of attachment belongs to, the handover can be either horizontal or vertical. If both point of attachment have same access networks (For ex: Both WLAN or Both cellular) then it is called *Horizontal Handover*. If they belong to different access networks, then it known as *Vertical Handover*. Also the handover can be classified as *Hard Handover* and *Soft Handover*. A handover is hard if the newly chosen target network is engaged only after releasing the existing network channel. While, a simultaneous connection is made between the existing and target access networks in case of a soft handover. The thesis work primarily focuses on horizontal soft handover. However the work can be extended to vertical handover with certain modifications.

## 1.2 Classification of Handover Algorithms

Various handover algorithms have been proposed previously. They are mainly classified into four categories: RSS based, Bandwidth based, Cost function based and Combination algorithms [4]. In RSS based algorithms, the RSS value received at the MT is considered as the handover decision criterion. If the RSS value from the new network is above certain threshold(static or dynamic), then handover occurs. The available bandwidth for an MT is considered as the decision criterion for bandwidth based algorithms. The cost based algorithms involve monetary cost or power consumption as the decision criterion. Combination algorithms use machine learning techniques such as fuzzy logic for handover decision process. With numerous handover algorithms available, it is very important to compare their performances to avoid heavy packet loss and achieve better Quality of service.

## 1.3 Handover Performance Evaluation Metrics

### 1.3.1 Types of Evaluation Metrics

Performance of handover algorithms can be quantitatively compared by various performance evaluation metrics [4]. As suggested in [1], WLAN usage efficiency can be used as a metric to measure the performance of a handoff algorithm. The usage efficiency is defined as the ratio of WLAN is actually used to that of WLAN may be usable. In this work, we provide an analytical framework to compute the usage efficiency by considering both the load on the APs and the soft handover for a specific data rate request of the MT. The approach we have taken to compute this usage efficiency is described as follows. In WLAN each MT is associated with an AP at certain maximum data rate which primarily depends on its distance from the serving AP. The current load of an AP depends on the number of MTs already associated with that AP and the rates at which they are associated. The effective throughput that an MT will get from an AP depends on the current load of that AP and the rate with which the MT will be associated to that AP. Thus the maximum data rate at which an MT will be associated with an AP must be sufficient enough to provide the effective throughput higher than its requested data rate. This maximum data rate can be translated into a circular region centered around an AP within which the requested data rate may be satisfied, if the MT is associated to that AP. For an MT with a certain requested data rate, different APs will have different radii of the circular regions depending on their current loads. The union of the areas of all such circular regions is then defined as the WLAN usable region for the MT. However, the WLAN area that will actually be used by the MT depends on a particular handoff algorithm. For the purpose of this analysis we have considered an algorithm which is based on the time an MT will spend inside the WLAN usable area. This residence time is calculated by considering both the random waypoint mobility model and smooth random waypoint mobility model. Accordingly the WLAN used radii for all the APs is computed.

Besides usage efficiency, few other metrics seem to have a significant impact on performance of handover algorithms. One such metric is handover failure probability. Failure probability can be defined as the probability that a handover process, when initiated, would terminate before completion. The magnitude of the failure probability mainly depends on the mobility model adopted by the MT along with the handover algorithm. In this thesis, we have tried to find a lower bound on failure probability considering the mobility of the MT irrespective of the handover algorithm adopted. That is our claim is every handover algorithm would have a failure probability of at least same as the lower bound. Further analysis show a drastic increase in this lower bound with increase in load and requested data rate. We have considered the three circle intersection problem to find the lower bound on failure probability for a soft handover process. We have also found a lower bound on the unnecessary handover probability. Unnecessary handover probability is the probability that a handover to the previous point of attachment required within a certain time interval. Again this lower bound can be found in a similar way as that of failure probability.

### 1.3.2 Dependency on load and soft handover

The handover evaluation metrics mentioned above depend on several factors. The MT tends to get lesser data rate as it moves away from the AP and various path losses cause the received power at the MT decrease with distance. Therefore to achieve the requested data rate, a simultaneous connection under soft handoff may be established with another AP till the user moves out entirely of the WLAN coverage area. The data rate an MT gets from an AP also depends on the load on that AP. Hence besides the choice of handover algorithm, the load on each of the APs plays a significant role for providing the seamless data transmission to the concerned MT.

The overall aim of the thesis is to analyze the impact of load, requested data rate and soft handover on various handover performance evaluation metrics. The scenario involves multiple APs and also considers different mobility models for the MT. The results seem promising and could be extended to scenarios involving vertical handover between APs and base stations.

# Chapter 2

# Related Work and Contributions

## 2.1 State of the Art

### 2.1.1 Handover Algorithms

In order to have proper network selection and handoff decision across multiple networks, many handoff algorithms such as [16], [19], [21], [22], [35] and [36] have been proposed. Along with the network and transport layer functionalities, determining the proper handover triggering instant is very crucial which can be a deciding factor to evaluate the performance of a handoff algorithm [23], [24]. Initially much of the focus for handover decision was on RSS measurement. In [9], the RSS from the current AP is compared with that of other APs for handover decision. Gradually other parameters such as available bandwidth were considered [10]. In some algorithms, both bandwidth and RSS information were used in the decision process [11]. Some other algorithms combined monetary cost and power consumption in a cost function and the handover decision is made by comparing the result of this function for the candidate networks [12].

### 2.1.2 Previous Performance Evaluation Frameworks

Previously many analytical frameworks have been proposed to evaluate the performance of different handover algorithms. In [6], an analytical framework has been proposed to evaluate various vertical handoff algorithms based on TCP and UDP throughput. A framework based on stochastic process algebra has been proposed in [2]. In [14], a comparison of the handoff algorithms based on network switching costs and QoS parameters have been proposed. In [13], a new admission control scheme have been proposed satisfying the hard constraints on handoff failure probability. A framework based on the decision delay and the number of handoffs has been proposed in [18]. In [15], analytical results for handoff probability for wireless networks have been proposed under a generally distributed call holding and the cell residence time. In [5] a markov-based framework has been proposed to model the handover process for the mobile user and derive an optimal context-dependent handover criterion. An analytical framework to evaluate the performance of IPv6-based mobility management protocols have been proposed in [20]. It has been shown in [1] that the WLAN usage efficiency can be a good metric to analyze the performance of a handoff algorithm.

### 2.1.3 Limitations of Previous Frameworks

One major limitation of the above studies is that the performance evaluation do not take account the requested data rate of the MT along with load and soft handover. However, consideration of requested data rate is an important factor for applications having strict rate requirement. In a multi-AP scenario, load on each of the APs can drastically reduce the effective throughput to an MT. Thus to ensure that the MT's requested data rate is satisfied, the effect of loads on each of the APs must be considered. A soft handover during network selection virtually eliminates unnecessary packet loss and improves overall connectivity [37]. Many practical schemes have been proposed for soft handover through rake combining [3]. Connectivity time of an MT with the help of soft handover may be increased significantly [34]. Also, under heavy load situation, soft handoff can greatly improve the effective throughput.

## 2.2 Our Contribution

In this thesis, the focus is to evaluate the performance metrics by taking care of both the load and soft handover for a specific data rate request of the MT. The contributions of our work are summarized as follows:

- Considering a certain load on each of the AP, the WLAN usable radii are evaluated for all the APs.
- A dwelling time based handoff algorithm is considered for the purpose of this analysis. Separate analysis have been carried out for the MT in random waypoint mobility model and a more realistic smooth random waypoint mobility model. Considering this handoff algorithm and the corresponding mobility model, the WLAN used radii for all the APs are computed .
- Usage efficiency is evaluated in terms of the ratio of WLAN used to WLAN usable area.
- Considering random way point mobility model, lower bound on handover failure probability is evaluated. Similarly a lower bound on unnecessary handover probability is evaluated.
- With an increase in the load on the APs, the effective throughput of an MT may decrease drastically thereby making it difficult to satisfy the requested data rate of the MT. In such a situation, soft handover with another AP may provide the required data rate to the MT. Effects of both load and soft handover on the above mentioned metrics have not been analyzed previously. Hence an analytical framework has been provided to measure these metrics under both load condition and soft handover. The effect of the velocity of the MT is also analyzed.

# Chapter 3

# Model Overview

## 3.1 System Model

In our framework, $n$ $APs$ are randomly placed inside a square grid of length $a$. Suppose the co-ordinates of the APs are $(x_1, y_1), (x_2, y_2) \cdots (x_n, y_n)$. Let each $AP$ be already associated with some MTs at certain maximum data rates. An MT moves inside the square grid requesting a specific data rate. For a certain requested data rate of an MT and a certain current load on an AP, the WLAN usable radius for that AP may be determined. Let $r_j^{usable}$ be the WLAN usable radius of $AP_j$. In the next sections we will compute $r_j^{usable}$ for each $AP_j$ by considering their current loads. After computing these radii, we will get $n$ circles $C_1, C_2 \cdots C_n$ with radii $r_1^{usable}$,$r_2^{usable}$ $\ldots$ $r_n^{usable}$ respectively. The WLAN usable region can then be expressed as the union area of all such circles. In a similar way, the WLAN used radii for all the APs can be computed by considering a particular handoff algorithm. Thus the WLAN usage efficiency can be computed. A Similar approach was followed to evaluate a lower bound on handover failure probability and unnecessary handover probability.

## 3.2 Throughput and MAC scheduling

Let $m_j$ be the number of MTs associated with $AP_j$. Then as per the random polling access medium access control (MAC) scheduling, the effective throughput $T_j$ obtained by all the MTs associated with $AP_j$ is given by [26]:

$$T_j = \frac{1}{\sum_{i=1}^{m_j} \frac{1}{r_i}} \tag{3.1}$$

where $r_i$ is the maximum data rate at which $MT_i$ is associated with $AP_j$, $1 \leq i \leq m_j$.

## 3.3 Defining Load

As evident from our previous discussion, load on an AP have a significant impact on the handover performance evaluation metrics. Load can be defined in several ways. Number of MTs associated with an AP can be a load metric [27]. But different MTs may be associated with the AP at different data rates. So for a fixed number of MTs, a low data rate association may lead to less traffic and hence less load on the AP. So defining load as a function of only the number of MTs associated with it, may not be appropriate. Another metric for load can be channel utilization [28]. But again transmission capabilities of the APs may vary and thus it may not be considered as an appropriate metric. In this work, we have considered the effective throughput provided by an AP to all its associated MTs as the load metric [29]. We have defined inverse of the effective throughput as load since an increase in load decreases the effective throughput.

Current load $L_j$ on $AP_j$ is given by:

$$L_j = \frac{1}{T_j} = \sum_{i=1}^{m_j} \frac{1}{r_i} \tag{3.2}$$

It is to observe that the load definition provided in the model is independent of the MAC scheduling adopted. For example, for proportionally fair MAC scheduling only the expression for $T_j$ in Equation (3.1) changes. The model is generic for all MAC scheduling approaches.

## 3.4 Mobility Model

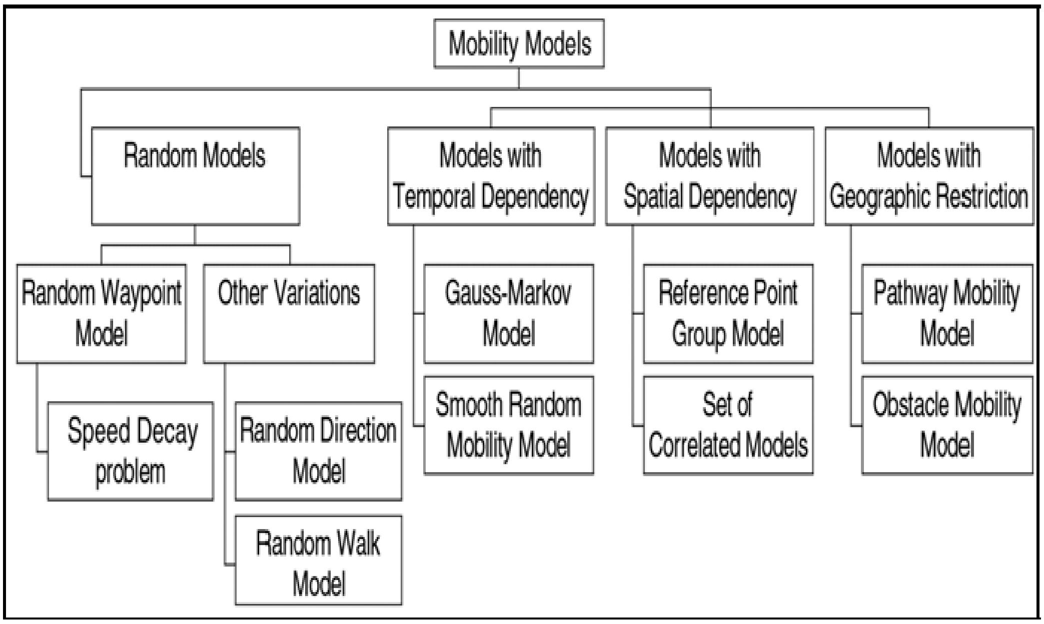


Fig. 3.1: Classification of mobility models [7]

In Figure 3.1, various mobility models are developed based on specific mobility characteristics of the MTs [7]. A model in which the movement of an MT is likely to be affected by its movement history, is known as, mobility model with temporal dependency. In mobility models with spatial dependency, the MTs tend to travel in a correlated manner. Another class is the mobility model with geographic restriction, where the movement of nodes is bounded by streets, freeways or obstacles.

The mobility model adopted in the thesis is the most commonly used random waypoint mobility model. A more realistic smooth random waypoint mobility model has also been considered.

## 3.5 Pathloss Model

The path loss is the difference between the transmitted power and the received power. Different pathloss models have been proposed for wireless networks. They can mainly be categorized into three groups as follows [25].

- **Empirical models :** Based on measurement data, these models calculate the pathloss. These models are simple with few parameters and use statistical properties. One of the fine and widely used example is the HATA model.
- **Semi-deterministic models :** These models are also based on empirical models but with deterministic aspects.
- **Deterministic models :** These models are site-specific and require enormous number of geometry information about the cite. These also require very high computational effort.

The pathloss model adopted for the thesis is an empirical model known as the $JTC$ indoor pathloss model [8] given by:

$$PL = A + B\log(r) + L(n) \tag{3.3}$$

where the parameters $A$, $B$ and function $L$ are specified in Table 3.1 and $r$ is the Euclidean distance between the test point and $AP$ in metres.

## 3.6 Geometric Interpretation

Finding union of the area of circles is a standard computational geometry problem. An $O(nlog^2n)$ time deterministic algorithm was proposed by M. Sharir [39] based on

| Parameters | Residence | Office | Complex |
|---|---|---|---|
| A(dB) | 38 | 38 | 38 |
| B(dB) | 28 | 30 | 22 |
| L(n) | 4n | 15+4(n-1) | 6+3(n-1) |

Table 3.1: JTC Pathloss model Parameters

modified voronoi diagram. Paul G. Spirakis also presented an $O(n^2)$ time deterministic algorithm and an $O(n)$ time probabilistic algorithm to compute such area [40]. We have adopted the probabilistic algorithm proposed in [40] which uses linear time Monte carlo simulation method [31]. To find lower bounds on failure probability and unnecessary handover probability, a model with three circle intersection problem is adopted [42].

# Chapter 4

# Evaluation of WLAN Usage Efficiency

## 4.1 Evaluation of WLAN usable radius

Let the APs be already connected to some of the MTs with certain maximum data rates. The maximum data rate at which a requesting MT will be associated with the AP depends on the Euclidean distance between them. But the actual throughput it gets from the AP depends on number of MTs already associated with the AP and their corresponding maximum data rates. The effective throughput that the requesting MT will get from the AP may be considerably less as compared to the maximum data rate with which it will be associated under heavy load condition. So for an MT, the requested data rate can only be satisfied if the effective throughput after the association becomes more than the requested. Hence we can easily state that an MT requesting a data rate $R$ can only be served by $AP_j$ if:

$$R \leq \frac{1}{L_j + \frac{1}{Y_j}} \tag{4.1}$$

where $Y_j$ is the maximum data rate with which the requesting MT will be associated with $AP_j$ and $L_j$ is the current load of $AP_j$ as defined in Equation (3.2). To calculate minimum such $Y_j$, equality in Equation (4.1) must hold. Hence from Equation (4.1) we can easily compute $Y_j$ as :

$$Y_j = \frac{R}{1 - L_j R} \tag{4.2}$$

It is clear from Equation (4.2) that for $Y_j$ to be positive,

$$R < 1/L_j \tag{4.3}$$

This puts a upper bound on requested data rate for a given current load of an AP.

The value of $Y_j$ computed in Equation (4.2) can be translated to a circular region around $AP_j$ within which the moving MT will definitely get the requested data rate $R$. Above mentioned radius can be treated as WLAN usable radius of $AP_j$ for the MT. We now compute this radius based on two different approaches.

### 4.1.1 RSS based approach

Many handoff decision algorithms consider received signal strength (RSS) at the MT as the handoff decision indicator. For a given value of maximum data rate, the RSS value required at the MT can be computed using standard mapping between RSS values and maximum data rates available for different WLAN standards such as IEEE 802.11a/b/g [33]. Let $\mathcal{I}(Y)$ be such mapping that returns the RSS value at the MT to achieve a maximum data rate of $Y$. Hence for $AP_j$ to satisfy a requested data rate of $R$ under current load $L_j$, the RSS value at the MT must be :

$$RSS = \mathcal{I}(Y_j) \tag{4.4}$$

where $Y_j$ is the maximum data rate given in Equation (4.2).

As the MT moves away from the AP, the received power at the MT decreases and hence the RSS value at the MT also decreases. The RSS at the requesting MT may therefore depend on the path loss and the propagation model adopted for analysis. If the transmitted power at the AP is $P_t$ and $PL$ is the path loss then the received power

$P_r$ is given by :

$$P_r = P_t - PL \tag{4.5}$$

Adopting JTC path loss model, the path loss $PL$ at a distance $r$ meters from an AP is given by:

$$PL = A + B\log(r) + L(n) \tag{4.6}$$

where the parameters $A$, $B$ and function $L$ are specified in Table 3.1. Combining Equations (4.5) and (4.6), we get:

$$RSS = P_t - A - B\log(r) - L(n) \tag{4.7}$$

The WLAN usable radius may be defined as the radius of the circular region around an AP such that anywhere inside the region, the AP can serve the MT with the requested data rate. Let $r_j^{usable}$ be such radius for $AP_j$. Combining Equations (4.4) and (4.7) and putting $r = r_j^{usable}$ we get:

$$r_j^{usable} = 10^{(P_t - A - L(n) - \mathcal{I}(Y_j))/B} \tag{4.8}$$

**Remark 1.** *It may be noted that the computation of usable radius can be done for different wireless standards just by adopting a different mapping function $\mathcal{I}$. Moreover, the analysis can be done for other path loss model as long as $PL$ is a function of distance.*

### 4.1.2 SINR based approach

The usable radius around an AP can also be determined based on the signal to interference plus noise ratio (`SINR`) received at the requesting MT. Let $\gamma_j$ be the SINR received by the MT from $AP_j$. We can represent $\gamma_j$ as:

$$\gamma_j = \frac{P_j C_j}{N + \sum_{k \in S_{AP} \setminus AP_j} P_k C_k} \tag{4.9}$$

where $P_j$ is the transmitting power of $AP_j$, $S_{AP}$ is the set of APs, $N$ is the background noise power at the receiver's end, $C_j$ is the channel gain between the MT and $AP_j$. The channel gain between an MT and an AP is a decreasing function of the Euclidean distance between them. Let $\mathcal{G}$ be such a function. Hence Equation (4.9) can be rewritten as:

$$\gamma_j = \frac{P_j \mathcal{G}(d_j)}{N + \sum_{k \in S_{AP} \setminus AP_j} P_k \mathcal{G}(d_k)} \tag{4.10}$$

where $d_j$ is the distance between $AP_j$ and the MT. Maximum achievable data rate for the given carrier bandwidth and SINR can be determined with the help of Shannon's capacity formula. The maximum achievable data rate $Y$ that an MT gets from an AP is given by:

$$Y = W \log_2(1 + \frac{\gamma}{\Gamma}) \tag{4.11}$$

where $W$ is the carrier bandwidth, $\Gamma$ is the dB gap between uncoded quadrature amplitude modulation (QAM) and channel capacity, minus the coding gain and $\gamma$ is the SINR received by the MT from the AP.

Let $\gamma_j^{req}$ be the minimum SINR required by the MT from $AP_j$ to achieve the data rate $Y_j$ as mentioned in Equation (4.2). Clearly from Equation (4.11) $\gamma_j^{req}$ is given by:

$$\gamma_j^{req} = \Gamma(2^{Y_j/W} - 1) \tag{4.12}$$

So in this case WLAN usable radius $r_j^{usable}$ would be the radius of the circular region around $AP_j$ such that at any point inside the region the MT will be able to get at least $\gamma_j^{req}$ SINR as given in Equation (4.12). We now state the following theorem to find

$r_j^{usable}$.

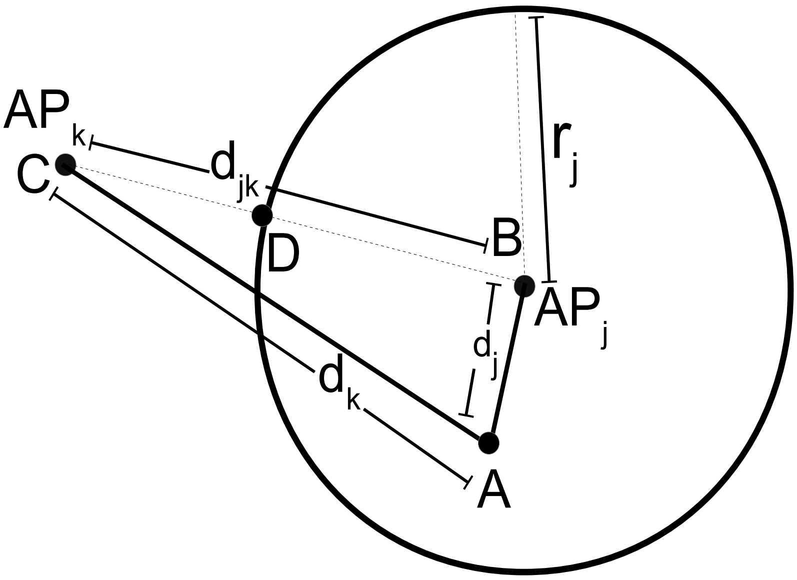


Fig. 4.1: SINR based usable radius

**Theorem 1.** *The WLAN usable radius of $AP_j$ can be obtained by solving the following equation for $r_j^{usable}$:*

$$\gamma_j^{req} = \frac{P_j \mathcal{G}(r_j^{usable})}{N + \sum_{k \in S_{AP} \setminus AP_j} P_k \mathcal{G}(max(d_{jk} - r_j^{usable}, 0))} \tag{4.13}$$

*where $d_{jk}$ is the distance between $AP_j$ and $AP_k$.*

*Proof.* Let $B$ be the position of $AP_j$. Now consider the circular region with radius $r_j$ around $B$ as shown in Figure 4.1. Let $A$ be any point on or inside the circular region, representing the current position of the MT. Clearly for any such position of $A$, the *maximum* distance of $A$ from $B$ can be $r_j$. That is, $d_j \leq r_j$. Hence we get:

$$\mathcal{G}(d_j) \geq \mathcal{G}(r_j) \tag{4.14}$$

since $\mathcal{G}$ is a decreasing function of the Euclidean distance.

Let $C$ be the position of $AP_k$, where $k \in S_{AP} \setminus AP_j$. Let us first consider the case where $C$ is located outside the circle. Let $D$ be the point of intersection of the line segment $BC$ with the circle as shown in Figure 4.1. The length of line segment $CD$ is $d_{jk} - r_j$. For any position of $A$ on or inside the circular region, the *minimum* distance of $A$ from $C$ is $d_{jk} - r_j$. We now consider the case where $C$ is located on or inside the circle. In this case, the *minimum* distance of $A$ from $C$ can be 0. Considering both the cases, for any position of $A$, the minimum distance of $A$ from $C$ is $max(d_{jk} - r_j, 0)$. That is, $d_k \geq max(d_{jk} - r_j, 0)$. This implies:

$$\mathcal{G}(d_k) \leq \mathcal{G}(max(d_{jk} - r_j, 0)) \quad \forall k \in S_{AP} \setminus AP_j \tag{4.15}$$

since $\mathcal{G}$ is a decreasing function of Euclidean distance. From Equation (4.10) using Equations (4.14) and (4.15) we get:

$$\gamma_j \geq \frac{P_j \mathcal{G}(r_j)}{N + \sum_{k \in S_{AP} \setminus AP_j} P_k \mathcal{G}(max(d_{jk} - r_j, 0))} \tag{4.16}$$

From Equation (4.16) it follows that if

$$\frac{P_j \mathcal{G}(r_j)}{N + \sum_{k \in S_{AP} \setminus AP_j} P_k \mathcal{G}(max(d_{jk} - r_j, 0))} \geq \gamma_j^{req}$$

then $\gamma_j \geq \gamma_j^{req}$, as required. It can be seen that $\frac{P_j \mathcal{G}(r_j)}{N + \sum_{k \in S_{AP} \setminus AP_j} P_k \mathcal{G}(max(d_{jk} - r_j, 0))}$ decreases as $r_j$ increases. Hence the value of $r_j$ will be maximum when $\frac{P_j \mathcal{G}(r_j)}{N + \sum_{k \in S_{AP} \setminus AP_j} P_k \mathcal{G}(max(d_{jk} - r_j, 0))} = \gamma_j^{req}$. So the WLAN usable radius $r_j^{usable}$ of $AP_j$ can be obtained by solving the equation stated in Equation (4.13) for $r_j^{usable}$. □

**Remark 2.** *Note that for different path loss models, only the channel gain function $\mathcal{G}$ differs. Hence the analysis can be done for any path loss model as long as their* *corresponding channel gain function is a decreasing function of Euclidean distance.*

**Remark 3.** *In our framework we have assumed the WLAN usable region to be circular. Note that more accurate usable region may be obtained through exact computation of the channel gains. But the region so obtained may not be in any regular shape. Moreover, analytically computing the area of such arbitrary shapes may be very difficult.*

## 4.2 Effect of soft handover

If an MT is not within the usable radius of any of the APs then it can not be served by any of them. Hence an outage will occur. But it might be possible that two APs simultaneously may be able to provide the requested data rate to the MT. Such a simultaneous connection establishment is the basis of soft handover mechanism. The requested data rate $R$ may be split into two separate streams of $R/2$ each and then combined at the rake receiver using QAM technique.

The WLAN usable radius for a requested data rate of $R/2$ for $AP_j$ can be computed by replacing $R$ by $R/2$ in Equation (4.2). So for $AP_j$ we get :

$$Y_j = \frac{R}{2 - L_j R} \tag{4.17}$$

where $Y_j$ is the maximum data rate at which the MT must be associated with $AP_j$ in order to satisfy the requested data rate of $R/2$. Proceeding as before (as mentioned in subsections 4.1.1 or 4.1.2) we can compute the usable radius for the above calculated value of $Y_j$. Let this radius be $R_j^{usable}$. Similarly we can compute the usable radius $R_k^{usable}$ for a requested data rate of $R/2$ for $AP_k$. Clearly $R_j^{usable} \geq r_j^{usable}$ and $R_k^{usable} \geq r_k^{usable}$.

Let us consider the region of intersection of the outer circles with radii $R_j^{usable}$ and $R_k^{usable}$ (as shown by region III in Figure 4.2). In this region the MT can get a requested data

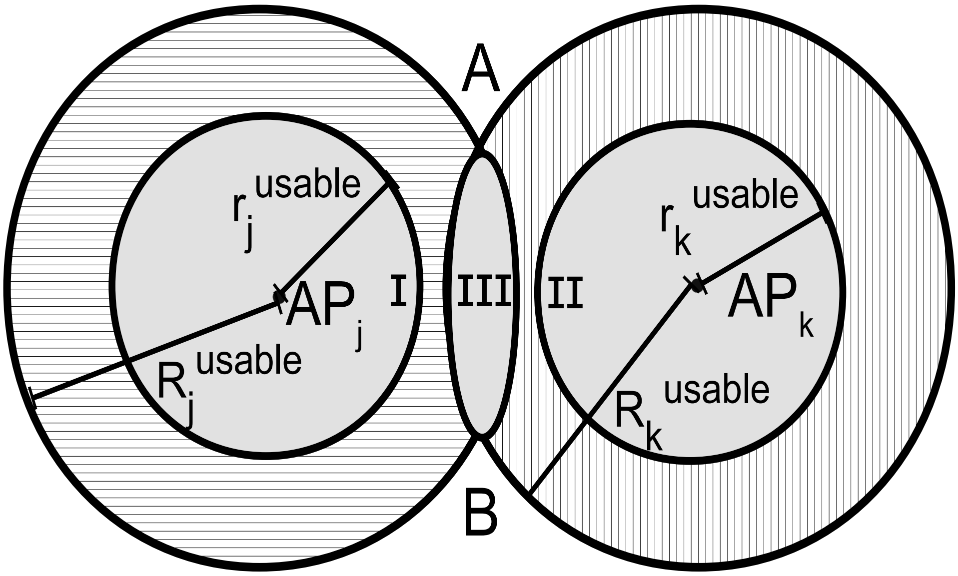


Fig. 4.2: Evaluation of usable region

rate of $R/2$ from both $AP_j$ and $AP_k$. The data received at a rate of $R/2$ from both the APs can be combined at the MT by QAM technique to achieve the requested data rate of $R$. Hence this region of intersection can be added to the overall WLAN usable region as within this region the requested data rate of the MT can be satisfied under soft handover.

## 4.3 Evaluation of WLAN used radius

As discussed before, the evaluation of WLAN usable area is independent of any handover algorithm or the user mobility model as it gives the theoretical maximum area that can be used by an MT depending on its requested data rate. However, the computation of used area actually depends on a particular mobility model and the handover algorithm adopted. When the handoff decision is taken, a handover delay (say $t_{ho}$) occurs in which WLAN is not utilized, i.e., no transmission of packets take place. This time interval can be thought of the portion where WLAN was usable but was not used. Excluding such time intervals we can compute how much time WLAN was actually used. As WLAN used area depends on both handover algorithm and mobility model of the AP, we can define the used area as follows.

Let $\mathcal{S}$ be the handover success function which returns the probability that the MT will take a decision to handover to the concerned AP and let $\mathcal{D}$ be distance function which returns the distance between the AP and the point the MT reaches after spending a time period of $t_{ho}$ since triggering the handover. If $M$ represents the set of parameters corresponding to the concerned mobility model and $H$ represents the handover decision parameters, then we can define the WLAN used radius for an AP as :

$$\begin{aligned} r^{used}(M,H) &= \mathcal{D}(M) \times \mathcal{S}(M,H) + 0 \times (1 - \mathcal{S}(M,H)) \\ &= \mathcal{D}(M)\mathcal{S}(M,H) \end{aligned} \tag{4.18}$$

**Remark 4.** *It is to be noted that for dwelling time based handoff algorithms,* $\mathcal{S}(M,H)$ *is either 0 or 1 and for hysteresis based handoff algorithms,* $\mathcal{S}(M,H)$ *is in between* 0 *and* 1*. This is because of the fact that, in case of dwelling time based algorithms, given a particular mobility model we can accurately determine the time the MT will spend inside the WLAN region. And hence comparing it to a particular time threshold will give us whether to hand-in at or not. But for hysteresis based algorithms, we may not be able to exactly determine the current RSS values which depend on other environmental factors also.*

We now evaluate both $\mathcal{S}(M,H)$ and $\mathcal{D}(M)$ for different mobility models and handoff algorithm.

### 4.3.1 Handover triggering algorithm

For the analysis purpose, we have considered a dwelling time based handoff algorithm called *traveling distance prediction based heuristic* [41]. In this method, a dynamic time threshold is calculated and is compared with the predicted traveling time of the MT inside the WLAN using RSS measurement. Instead of predicting the traveling time through RSS measurement, we have evaluated it with the help of the concerned mobility model. In our framework, we evaluate the time interval for which the moving MT will stay inside the WLAN usable region of the AP. If it is above a certain threshold then we initiate the handoff. Otherwise the handoff is not initiated. Lets denote this threshold as $T_{WLAN}$. As per [41], $T_{WLAN}$ can be calculated as :

$$T_{WLAN} = \frac{2r_j^{usable}}{v} \sin\left(sin^{-1}\left(\frac{vt_{ho}}{2r_j^{usable}}\right) - \frac{\pi}{2}P\right) \tag{4.19}$$

where $t_{ho}$ is the handover delay, $P$ is the maximum tolerable handover failure probability and $v$ is the velocity with which the MT traverses through the WLAN usable region. So a handover to the AP is initiated if the MT spends more than $T_{WLAN}$ time inside the WLAN usable region of that $AP$. Hence we can define the handover success function $\mathcal{S}(M, H)$ as:

$$\mathcal{S}(M, H) = \begin{cases} 1, & \text{if } \mathcal{T}(M) \geq T_{WLAN} \\ 0 & \text{otherwise} \end{cases}$$

where $\mathcal{T}(M)$ returns the time MT has spent inside the WLAN usable region of the $AP$ under a particular mobility model. If the MT is not within $r^{usable}$ distance from any of the APs or $\mathcal{T}(M) < T_{WLAN}$ for all the APs then soft handover process may be initiated as mentioned in Section 4.2. In this case we need to check whether the moving MT will stay inside the area of intersection of any two APs for more than $T_{WLAN}$ duration. In the following sections we have derived methods to evaluate $\mathcal{T}(M)$ under different mobility models.

### 4.3.2 Mobility model for the MT

We have considered most widely adopted random way point mobility model and a more realistic smooth random way point model for evaluation of WLAN used radius. With minor modifications, the framework can easily be extended to other mobility models such as [17].

#### 4.3.2.1 Random waypoint mobility model

Under this mobility model, an MT uniformly at random chooses a point and moves towards it with a uniform velocity chosen from an interval $[v_{min}, v_{max}]$ as discussed in [38]. After reaching destination, it again repeats the same rule. Hence the parameters of this mobility model denoted by M (as discussed earlier) are the velocity (say $v$) of the MT and the trajectory (say $\psi$) it makes with the AP when it enters the periphery of the WLAN usable region of that $AP$.

Suppose the MT enters the usable region of $AP_j$ at position $A$ at time $t = 0$ as shown in Figure 4.3. Let $D$ be the position of the MT at time $t = t_{ho}$. Clearly, the actual data transmission takes place after time $t = t_{ho}$. Hence during the time MT is moving from $A$ to $D$, WLAN is not actually used. So the line segment $CD$ can be considered as the used radius for $AP_j$. Clearly for a particular velocity $v$ of the MT, the length of the line segment $AD = vt_{ho}$. From Figure 4.3 it is clear that the distance between the AP and the point the MT reaches after spending a time period of $t_{ho}$ since triggering the handover, i.e., $\mathcal{D}(M)$ is given by:

$$\mathcal{D}(M) = \sqrt{(r_j^{usable})^2 + v^2 t_{ho}^2 - 2(r_j^{usable}) v t_{ho} \cos(\psi)} \tag{4.20}$$

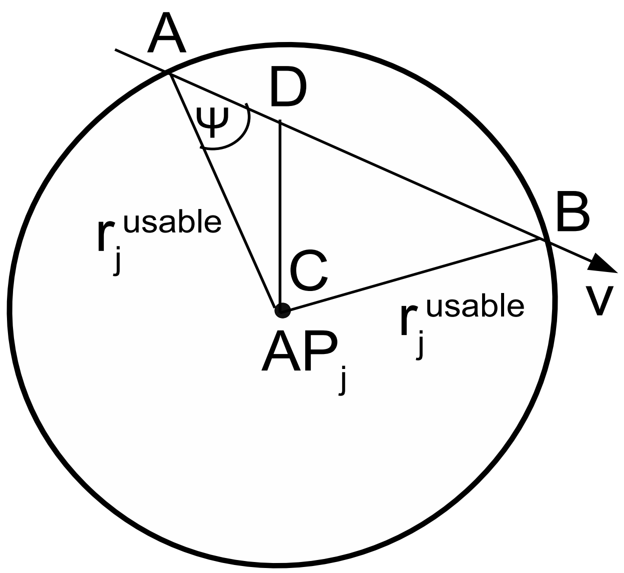


Fig. 4.3: Mobility under RWP

Similarly the time MT will spend inside the WLAN usable region of the $AP$, i.e., $\mathcal{T}(M)$ is given by:

$$\mathcal{T}(M) = \frac{2r_j^{usable}\cos\psi}{v} \tag{4.21}$$

Hence the handover success function $\mathcal{S}(M,H)$ is given by:

$$\mathcal{S}(M,H) = \begin{cases} 1, & \text{if } \frac{2r_j^{usable}\cos\psi}{v} \geq T_{WLAN} \\ 0 & \text{otherwise} \end{cases}$$

Let $V$ denote the set of all possible velocities of an $MT$ and $\Psi$ be the set of all possible trajectories then the average WLAN used radius for $AP_j$ can be computed by following the approach adopted in [1] as follows:

$$r_j^{used} = \sum_{\psi\in\Psi}\sum_{v\in V}\mathcal{D}(M)\mathcal{S}(M,H)P_{Vel}(v)P_{traj}(\psi) \tag{4.22}$$

where $P_{vel}$ and $P_{traj}$ are the probability distributions of velocity and trajectory of the

MT.

Similarly to consider the effect of soft handover we can put $R_j^{usable}$ in place of $r_j^{usable}$ in the above equations. The radius thus obtained is $R_j^{used}$ for $AP_j$.

#### 4.3.2.2 Smooth random waypoint mobility model

Though random waypoint mobility model is most widely adopted mobility model, the main issue with it is that the new choice for speed ($v$) and the direction ($\psi$) are not correlated to previous values. This may cause unrealistic movement behavior with sudden speed changes and sharp turnings. Hence a more realistic mobility model with a smooth change in velocity and direction was proposed [32]. In smooth random waypoint mobility model, the new choice of velocity and the trajectory are correlated to the previous values. Hence the parameters, $M$, for this mobility model include the velocity and trajectory of the MT before the choice (say $v_{old}$, $\psi_{old}$) and the velocity and trajectory of the MT after the choice has been made (say $v_{new}$, $\psi_{new}$). Also the acceleration of the MT during the velocity change and the rate of change of trajectory once the new trajectory is selected are considered as mobility parameters.

Suppose the MT enters the WLAN usable region of $AP_j$ at point $A$ at time $t = 0$ as shown in Figure 4.4. Suppose before entering at point $A$, the MT had a velocity $v_{old}$. Instead of an abrupt change to the new target velocity $v_{new}$, the MT gradually achieves the target velocity with an acceleration $a$. Once the target velocity $v_{new}$ is achieved, the MT continues to move with that velocity. Also let the trajectory of the MT before point $A$ be $\psi_{old}$. The MT continues to move in that trajectory for a duration of $t_{slot}$ covering a distance say $x_1$ and changes its trajectory at point $B$ to an intermediate trajectory $\psi_{int}$. Again it continues to move with trajectory $\psi_{int}$ for another $t_{slot}$ duration covering a distance say $x_2$. Finally it changes its movement to the target trajectory $\psi_{new}$ at point $C$

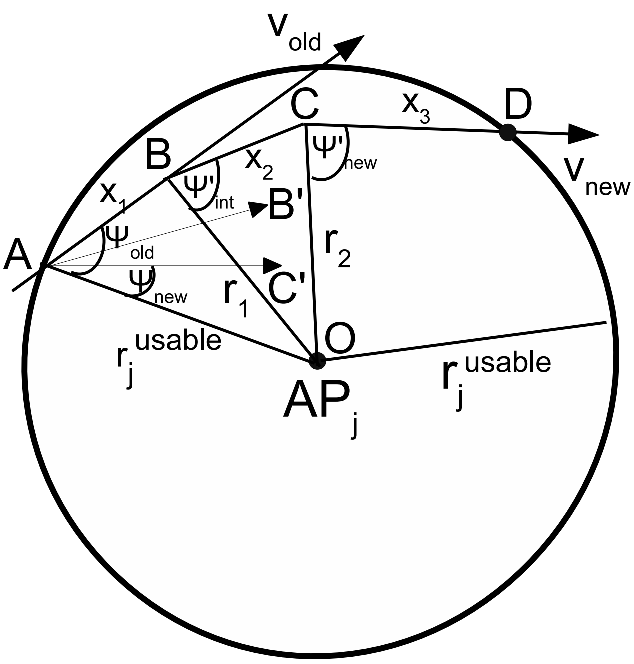


Fig. 4.4: Mobility under smooth RWP

and continues to move with that trajectory until a new change of the trajectory occurs. During this interval it crosses the WLAN usable region of the AP at point $D$ covering a distance say $x_3$. Though the trajectory of the MT gradually changes from $\psi_{old}$ to $\psi_{new}$, the MT has moved certain distance in this process. Hence the actual trajectory it subtends at points $B$ and $C$ are different from $\psi_{int}$ and $\psi_{new}$. Let these trajectories be $\psi^{'}_{int}$ and $\psi^{'}_{new}$ respectively as shown in Figure 4.4. Clearly $AB^{'} \parallel BC$ and $AC^{'} \parallel CD$.

Let $d(t)$ be the function which returns the distance traveled by the MT after a duration of $t$ sec. Clearly $d(t)$ is given by:

$$d(t) = \begin{cases} v_{old}t + \frac{1}{2}at^2, & \text{if } t_{acc} \leq t \\ v_{old}t_{acc} + \frac{1}{2}at_{acc}^2 + v_{new}(t - t_{acc}) & \text{otherwise} \end{cases}$$

where $t_{acc}$ is the duration for which the MT is accelerated and is equals to $\frac{v_{new}-v_{old}}{a}$. By applying the supplementary law of parallel lines and the cosine rule of triangles we get the following from Figure 4.4:

$$x_1 = d(t_{slot}) \tag{4.23}$$

$$x_2 = d(2t_{slot}) - x_1 \tag{4.24}$$

$$r_1 = \sqrt{(r_j^{usable})^2 + x_1^2 - 2(r_j^{usable}) x_1 \cos(\psi_{old})} \tag{4.25}$$

$$\psi_{int}^{'} = \pi - (\psi_{old} - \psi_{int}) - \cos^{-1}\left(\frac{x_1^2 + r_1^2 - (r_j^{usable})^2}{2x_1 r_1}\right) \tag{4.26}$$

$$r_2 = \sqrt{r_1^2 + x_2^2 - 2r_1 x_2 \cos(\psi_{int}^{'})} \tag{4.27}$$

$$x_{AC} = \sqrt{x_1^2 + x_2^2 - 2x_1 x_2 \cos\left(\psi_{int}^{'} + \cos^{-1}\left(\frac{x_1^2 + r_1^2 - (r_j^{usable})^2}{2x_1 r_1}\right)\right)} \tag{4.28}$$

$$\psi_{new}^{'} = \pi - 2\cos^{-1}\left(\frac{x_2^2 + x_{AC}^2 - x_1^2}{2x_2 x_{AC}}\right) - (\psi_{int} - \psi_{new}) - \cos^{-1}\left(\frac{x_2^2 + r_2^2 - r_1^2}{2x_2 r_2}\right) \tag{4.29}$$

$$x_3 = \frac{2r_2 \cos\psi_{new}^{'} + \sqrt{(2r_2 \cos\psi_{new}^{'})^2 - 4(r_2^2 - (r_j^{usable})^2)}}{2} \tag{4.30}$$

It is clear from Figure 4.4 that :

$$\mathcal{D}(M) =$$

$$\begin{cases} \sqrt{(r_j^{usable})^2 + x_{ho}^2 - 2(r_j^{usable}) x_{ho} \cos(\psi_{old})} & \text{if } t_{ho} \leq t_{slot} \\ \sqrt{r_1^2 + (x_h - x_1)^2 - 2r_1(x_h - x_1)\cos(\psi_{int}^{'})} & \text{if } t_{slot} \leq t_{ho} \leq 2t_{slot} \\ \sqrt{r_2^2 + (x_h - x_1 - x_2)^2 - 2r_2(x_h - x_1 - x_2)\cos(\psi_{new}^{'})} & \text{othewise} \end{cases}$$

where $x_h$ is the distance traveled by the MT in the time duration $t_{ho}$ and is equivalent to $d(t_{ho})$.

Let $d^{-1}(x)$ is the inverse function of $d(t)$ defined above. It basically returns the time taken by the MT to cover a distance of $x$ meters. Hence the time MT will spend inside the WLAN usable region of the $AP$, i.e., $\mathcal{T}(M)$ is given by:

$$\mathcal{T}(M) = d^{-1}(x_1 + x_2 + x_3) \tag{4.31}$$

where $x_1$, $x_2$ and $x_3$ are defined in equations (4.23), (4.24) and (4.30) respectively. Hence the handover success function $\mathcal{S}(M, H)$ is given by:

$$\mathcal{S}(M, H) = \begin{cases} 1, & \text{if } d^{-1}(x_1 + x_2 + x_3) \geq T_{WLAN} \\ 0 & \text{otherwise} \end{cases}$$

If $P_{vel}$ and $P_{traj}$ are the probability distributions of velocity and trajectory of the MT, $V$ denote the set of all possible velocities and $\Psi$ be the set of all possible trajectories then we can calculate the average WLAN used radius for $AP_j$ as:

$$r_j^{used} = \sum_{\psi_{old} \in \Psi} \sum_{v_{old} \in V} \sum_{\psi_{new} \in \Psi} \sum_{v_{new} \in V} \mathcal{D}(M)\mathcal{S}(M, H) \times P_{Vel}(v_{old}) P_{traj}(\psi_{old}) P_{Vel}(v_{new}) P_{traj}(\psi_{new}) \tag{4.32}$$

Considering the effect of soft handover, $R_j^{used}$ can be computed by replacing $r_j^{usable}$ with $R_j^{usable}$ in the above equations.

## 4.4 Evaluation of WLAN usage efficiency

In [1] WLAN usage efficiency is defined as the ratio of the total period that the MT is connected to the WLAN interface ($T^{used}$) to that the WLAN is usable ($T^{usable}$) by the MT.

$$\eta_{WLAN} = \frac{T^{used}}{T^{usable}} \tag{4.33}$$

Both $T^{usable}$ and $T^{used}$ can be expressed in terms of area.

In previous sections we evaluated the expressions for usable radius $r^{usable}$ for each AP. The union of the areas of all such circular regions can be taken as WLAN usable. Let us denote this area by $A^{usable}$. Besides this, we have also computed $R^{usable}$ for each AP in case of soft handover as mentioned in Section 4.2. Clearly area of intersection of outer circular regions of any two APs will also be included in WLAN usable area. Let the union of these intersection areas be denoted as $A^{usable}_{sho}$. Hence we can define the total WLAN usable area as :

$$A^{usable}_{total} = A^{usable} \cup \ A^{usable}_{sho} \tag{4.34}$$

As an example, consider two APs ($AP_j$ and $AP_k$) as shown in Figure 4.2. Clearly:

$$\begin{aligned} A^{usable} &= A^{region-I} \cup A^{region-II} \\ A^{usable}_{sho} &= A^{region-III} \\ A^{usable}_{total} &= A^{region-I} \cup A^{region-II} \cup A^{region-III} \end{aligned}$$

Above expressions can be generalized to n-AP scenario where union of the areas of circles can be computed by principle of inclusion and exclusion.

After evaluating $r^{used}$ and $R^{used}$ for each of the AP we can compute area of WLAN used region as:

$$A_{total}^{used} = A^{used} \cup \ A_{sho}^{used}$$

similar to the usable area computed previously.

Finally, we can compute WLAN usage efficiency as:

$$\eta_{WLAN} = A_{total}^{used} / A_{total}^{usable} \tag{4.35}$$

# Chapter 5

# Evaluation of Handover Failure Probability

A handover failure occurs when the handover is initiated but the target network does not have sufficient resources to complete it or when the MT moves out of the coverage of the target network before the process is finalized [4]. Considering the later case, we have estimated a lower bound on the handover failure probability for both hard and soft handover as follows. In both cases the minimum handover failure probability depends only on mobility model adopted, i.e., on the mobility parameters (denoted by $M$ as defined in earlier sections).

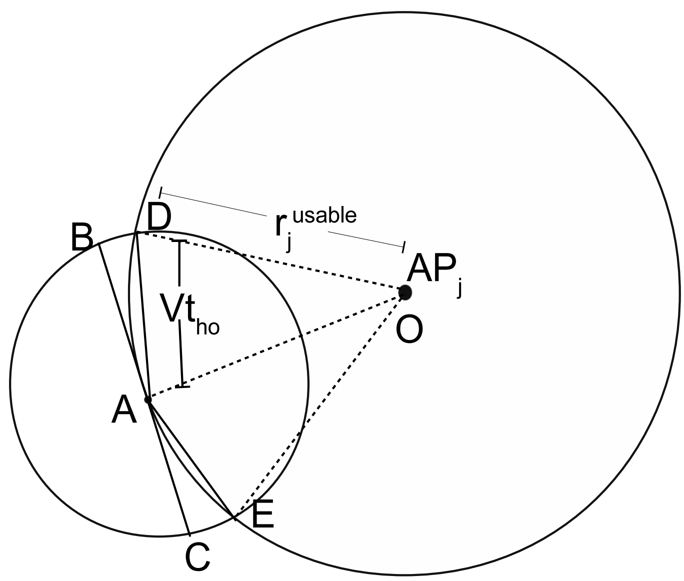


Fig. 5.1: Minimum handover (hard) failure probability

## 5.1 Evaluation for hard handover

Suppose an MT enters to the WLAN usable region of $AP_j$ at point $A$ as shown in Figure 5.1. Let us assume that the MT follows random waypoint mobility model. Let the velocity of the MT be $v$. From point $A$, the MT can move in any direction with the above velocity. The handover failure will occur if within the handover delay time period ($t_{ho}$), the MT moves out of the WLAN usable region of $AP_j$. So considering a circle around point $A$ with radius $vt_{ho}$, the sector $DAE$ inside the usable region of $AP_j$ gives the handover successful region. Here the target network is $AP_j$ and we have assumed that any handover algorithm is sensible enough to select $AP_j$ as target network only if the trajectory angles are from $-\pi/2$ to $\pi/2$. So the semicircle $BDEC$ can be considered as the sample space to evaluate the handover failure probability. Clearly:

$$\angle CAE = \pi/2 - \cos^{-1}\left(\frac{vt_{ho}}{2r_j^{usable}}\right) \tag{5.1}$$

Hence the minimum handover failure probability for $AP_j$ (denoted by $P_j^{hard}$) as a function of mobility parameters $M$ is given by:

$$\begin{aligned} P_j^{hard}(M) &= \frac{2\angle CAE}{\pi} \\ &= 1 - \frac{2}{\pi}\cos^{-1}\left(\frac{vt_{ho}}{2r_j^{usable}}\right) \end{aligned} \tag{5.2}$$

**Remark 5.** *Depending on the handover algorithm adopted, the area of handover successful region may get smaller which would only increase the handover failure probability. Hence the probability calculated in Equation (5.2) is minimum.*

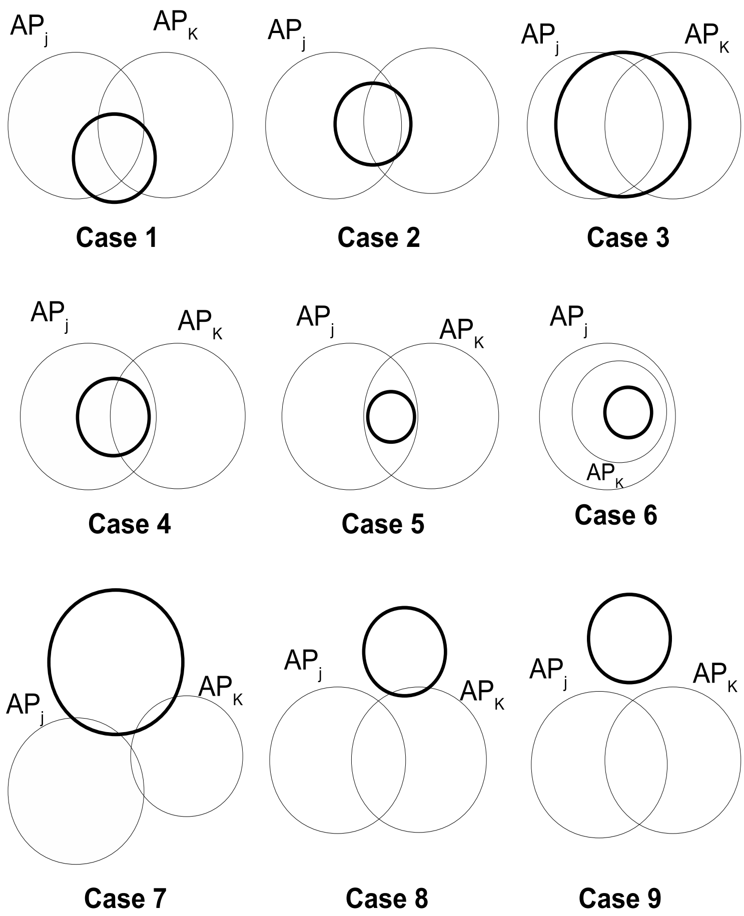


Fig. 5.2: Intersection area of 3 circles. The circle shown in bold is the circle with radius $vt_{ho}$

## 5.2 Evaluation for soft handover

Let us consider the effect of soft handover on minimum handover failure probability. Consider the soft handover between $AP_j$ and $AP_k$. As per [42], the area of overlap between three circles in a plane can have at most 9 different configurations as shown in Figure 5.2. Out of these configurations, depending on the velocity of the $MT$ and the position at which it enters to the soft handover region, the configurations (cases) $1, 2, 3$ and 4 are feasible. This can be explained as follows. Soft handover can occur only when $AP_j$ and $AP_k$ intersects. Hence configuration 6 is ruled out. Now we would check for soft handover only on periphery of region of intersection of $AP_j$ and $AP_k$, i.e., the center of the third circle with radius $vt_{ho}$ will only lie on periphery of region of intersection. Hence configurations 5,7,8 and 9 are ruled out and we are left with configurations $1, 2, 3$ and 4. Let us consider the soft handover shown in Figure 5.3. If the points of intersection of circles $AP_j$ and $AP_k$ are $A$ and $B$ with coordinates $(a_1, b_1)$ and $(a_2, b_2)$ respectively such that $b_1 > b_2$, then the parametric equation of the arc $AK'B$ is given by:

$$f(t) = (x_k + R_k^{usable} \cos t, y_k + R_k^{usable} \sin t), \quad \theta_1 \leq t \leq \theta_2 \tag{5.3}$$

where $(x_k,\, y_k)$ are the co-ordinates of $AP_k$ and

$$\theta_1 = sin^{-1}\left(\frac{b_1 - y_k}{R_k^{usable}}\right)$$
$$\theta_2 = sin^{-1}\left(\frac{b_2 - y_k}{R_k^{usable}}\right)$$

The parameter $t$ can be varied from $\theta_1$ to $\theta_2$ to obtain the center of the third circle for each $t$. For a particular $t$, the detection of the corresponding configuration along with the evaluation of minimum handover failure probability is discussed below. Same holds true for the other arc $AJ'B$.

### 5.2.1 Configuration 1

This configuration can easily be detected when point $A$ lies inside the third circle (of radius $vt_{ho}$) and point $B$ lies outside of this circle or vice versa as shown in Figure 5.3. Mathematically configuration 1 occurs if:

$$\sqrt{(a_1 - x_k - R_k^{usable} \cos t)^2 + (b_1 - y_k - R_k^{usable} \sin t)^2} < vt_{ho} \tag{5.4}$$

$$\sqrt{(a_2 - x_k - R_k^{usable} \cos t)^2 + (b_2 - y_k - R_k^{usable} \sin t)^2} > vt_{ho} \tag{5.5}$$

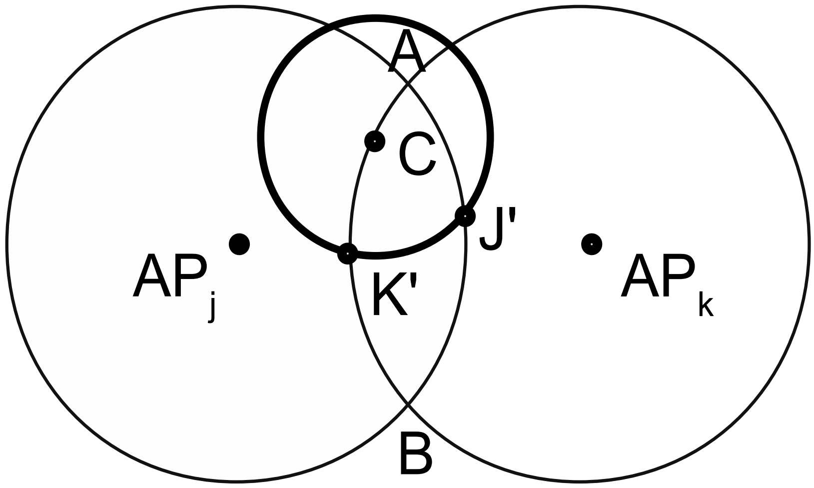


Fig. 5.3: Minimum handover (soft) failure probability

From Figure 5.3, it is clear that:

$$\angle K'CJ' = \cos^{-1}\left(\frac{2v^2t_{ho}^2 - (K'J')^2}{2v^2t_{ho}^2}\right) \tag{5.6}$$

where the chord length $K'J'$ can be found from the point of intersection of the third circle centered around $C$ with the two APs. Note that there may be two points of intersection between the third circle and any of the other two APs. Hence to find the co-ordinates of the points $K'$ and $J'$, distance from the other AP can be considered. The minimum handover failure probability in this case is given by:

$$P_{j,k}^{soft}(M,t) = 1 - \frac{\angle K'CJ'}{\pi} \tag{5.7}$$

### 5.2.2 Configuration 2

This configuration occurs when both point $A$ and $B$ lies outside of the third circle centered around $C$ and the circle around $AP_j$ intersects with the circle around $C$. Mathematically:

$$\sqrt{(a_1 - x_k - R_k^{usable} \cos t)^2 + (b_1 - y_k - R_k^{usable} \sin t)^2} > vt_{ho} \tag{5.8}$$

$$\sqrt{(a_2 - x_k - R_k^{usable} \cos t)^2 + (b_2 - y_k - R_k^{usable} \sin t)^2} > vt_{ho} \tag{5.9}$$

$$|R_j^{usable} - vt_{ho}| < \sqrt{(x_j - x_k - R_k^{usable} \cos t)^2 + (y_j - y_k - R_k^{usable} \sin t)^2} \tag{5.10}$$

$$|R_j^{usable} + vt_{ho}| > \sqrt{(x_j - x_k - R_k^{usable} \cos t)^2 + (y_j - y_k - R_k^{usable} \sin t)^2} \tag{5.11}$$

Let the points of intersection of the circle centered around $C$ and $AP_j$ are $J'$ and $J''$. Similarly let the points of intersection with $AP_k$ be $K'$ and $K''$. In this case, the minimum handover failure probability is given by:

$$P_{j,k}^{soft}(M,t) = 1 - \frac{1}{\pi}\cos^{-1}\left(\frac{2v^2t_{ho}^2 - (K'J')^2}{2v^2t_{ho}^2}\right) - \frac{1}{\pi}\cos^{-1}\left(\frac{2v^2t_{ho}^2 - (K''J'')^2}{2v^2t_{ho}^2}\right) \tag{5.12}$$

### 5.2.3 Configuration 3

This configuration occurs when both point $A$ and $B$ lies inside of the third circle centered around $C$. Mathematically:

$$\sqrt{(a_1 - x_k - R_k^{usable} \cos t)^2 + (b_1 - y_k - R_k^{usable} \sin t)^2} < vt_{ho} \tag{5.13}$$

$$\sqrt{(a_2 - x_k - R_k^{usable} \cos t)^2 + (b_2 - y_k - R_k^{usable} \sin t)^2} < vt_{ho} \tag{5.14}$$

And hence in this case:

$$P_{j,k}^{soft}(M,t) = 1 \tag{5.15}$$

### 5.2.4 Configuration 4

This configuration occurs when both point $A$ and $B$ lies outside of the third circle centered around $C$ and the circle around $C$ lies inside the circle around $AP_j$. Mathematically:

$$\sqrt{(a_1 - x_k - R_k^{usable} \cos t)^2 + (b_1 - y_k - R_k^{usable} \sin t)^2} > vt_{ho} \tag{5.16}$$

$$\sqrt{(a_2 - x_k - R_k^{usable} \cos t)^2 + (b_2 - y_k - R_k^{usable} \sin t)^2} > vt_{ho} \tag{5.17}$$

$$|R_j^{usable} - vt_{ho}| > \sqrt{(x_j - x_k - R_k^{usable} \cos t)^2 + (y_j - y_k - R_k^{usable} \sin t)^2} \tag{5.18}$$

This configuration is same as hard handover at $AP_k$ with radius as $R_k^{usable}$ instead of $r_k^{usable}$. Hence:

$$P_{j,k}^{soft}(M, t) = 1 - \frac{2}{\pi} \cos^{-1}\left(\frac{vt_{ho}}{2R_k^{usable}}\right) \tag{5.19}$$

## 5.3 Overall Minimum Handover Failure Probability

If $V$ is the set of all possible velocities of an $MT$ and $P_{vel}$ is the probability distribution of $V$, then the minimum handover failure probability for hard handover averaged over all possible velocities is given by:

$$P_j^{hard} = \sum_{v \in V} P_{Vel}(v) P_j^{hard}(M) \tag{5.20}$$

Similarly minimum handover failure probability for soft handover is given by:

$$P_{j,k}^{soft} = \sum_{v \in V} P_{Vel}(v) \min_t P_{j,k}^{soft}(M, t) \tag{5.21}$$

And the overall minimum handover failure probability can be evaluated as:

$$P = \min\left(\min_{j} P_j^{hard}, \min_{j,k} P_{j,k}^{soft}\right) \tag{5.22}$$

# Chapter 6

# Evaluation of Unnecessary Handover Probability

If the $MT$ is inside the WLAN cell for less than the sum of the handover time into ($t_{in}$) and out of ($t_{out}$) the WLAN cell then the handover to the WLAN cell becomes unnecessary [41]. Taking $t_{in} = t_{out} = t_{ho}$, a lower bound on unnecessary handover probability can be calculated both for hard handover and soft handover and the overall lower bound can be found the same way as described in Chapter 5 simply by replacing $vt_{ho}$ by $2vt_{ho}$ in the corresponding equations.

# Chapter 7

# Results and Discussions

In this chapter we have analyzed the impact of load and soft handover on various handover metrics. Also the impact of velocity on these metrics has been shown.

## 7.1 Model Setup

APs are placed within a $1000 \times 1000\ m^2$ grid with a minimum distance 30 $m$ within any two APs. Total number of APs is fixed to 25. Each of the AP has been given some load measured in terms of inverse of throughput (in s/MB). For the assigned load and a requested data rate both $r^{usable}$ and $R^{usable}$ is computed for each of the 25 APs. While computing $r^{usable}$ and $R^{usable}$ for an AP, both RSS and SINR based approach has been adopted as mentioned in 4.1.1 and 4.1.2. To compute the corresponding RSS values for different data rates 802.11$g$ standard has been adopted [33]. A depiction of the above setup is shown in Figure 7.1. The APs are shown as red cross marks and the inner black circles correspond to regions providing the requested data rate. The outer blue circular regions provide half of the requested data rate. Hence intersection of blue circular regions are soft handover regions.

The mobility parameters ($M$) for both random waypoint and the smooth random waypoint mobility models as well as the handover decision parameters ($H$) are shown in Table 7.1. The mobility parameters for smooth random waypoint mobility model are similar to those mentioned in [32].

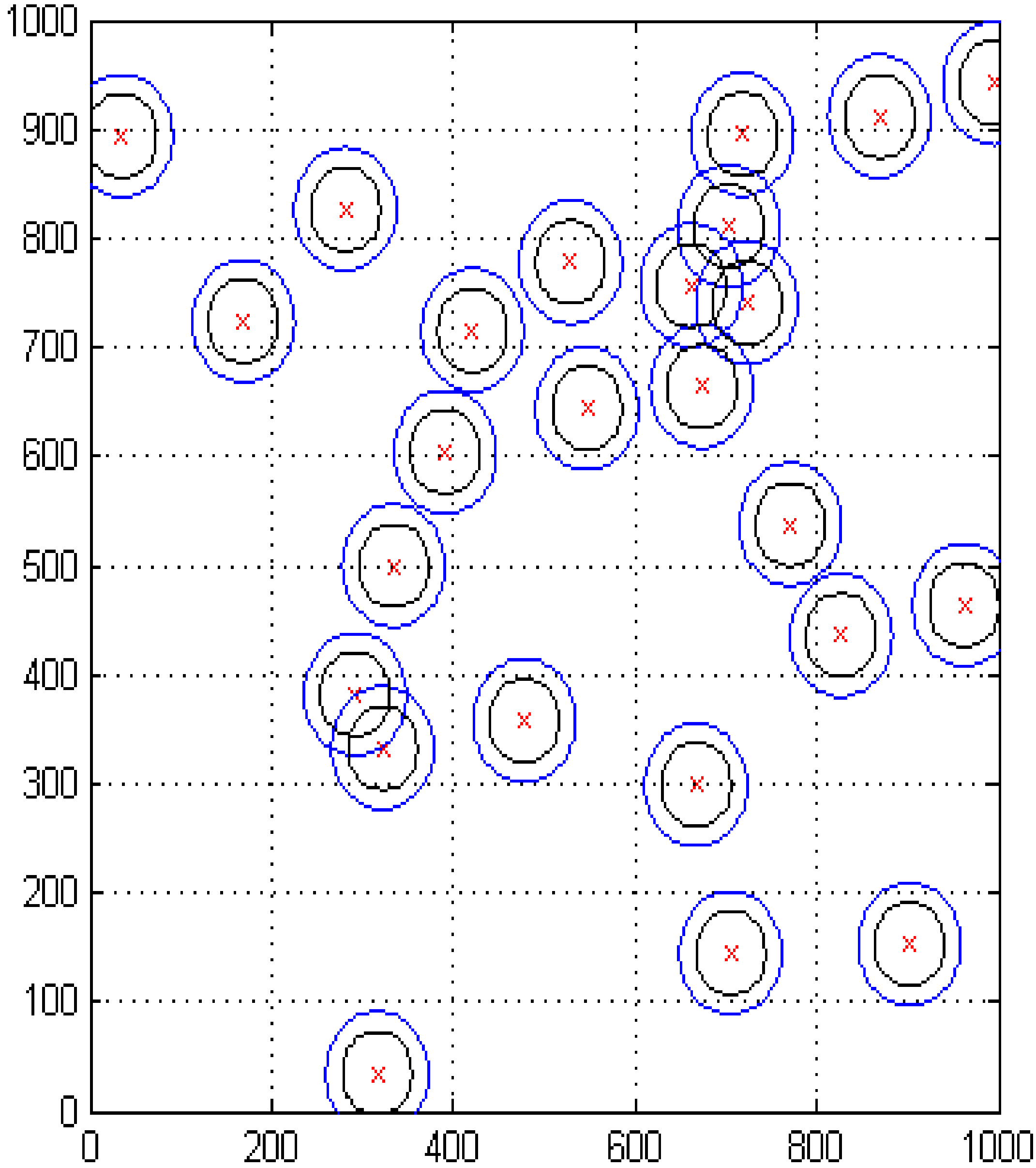


Fig. 7.1: Placement of APs

| | |
|---|---|
| Handover Failure Probability (P) | 0.002 |
| Handover delay ($t_{ho}$) | 200 ms |
| $v_{min}$ | 0 m/s |
| $v_{max}$ | 13.9 m/s |
| V | 3.475 m/s, 6.95 m/s<br>10.425 m/s, 13.9 m/s |
| acceleration (a) | $-4, -3.5, \cdots, 2.5\ m/s^2$<br>(with an interval of 0.5 $m/s^2$) |
| Time Slot ($t_{slot}$) | 100 ms |
| $\Psi$ | $0, \pi/20, \cdots, \pi/2$<br>(with an interval of $\pi/20$) |

Table 7.1: Handoff decision and mobility model parameters

After $r^{usable}$, $R^{usable}$, $r^{used}$ and $R^{used}$ has been computed for all the APs for a certain load, $A^{usable}_{total}$ and $A^{used}_{total}$ are computed by monte carlo simulation method. The result thus obtained has been averaged over thousand samples to attain maximum accuracy.

## 7.2 Load Versus Metrics

Clearly the load versus usage area curve (as shown in Figure 7.2) indicates that with an increase in load the usable area decreases drastically. This happens as both used and usable radii decreases due to load. An increase in load decreases effective throughput thereby decreasing both the radii. But in both cases soft handover adds to the total area thereby increasing it as compared to the case of without soft handover. From the figure, it is evident that the impact of soft handover becomes more prominent at heavy load situation. In this figure WLAN usable area is computed based on the RSS based approach. We have also considered the SINR based approach for computing the usable

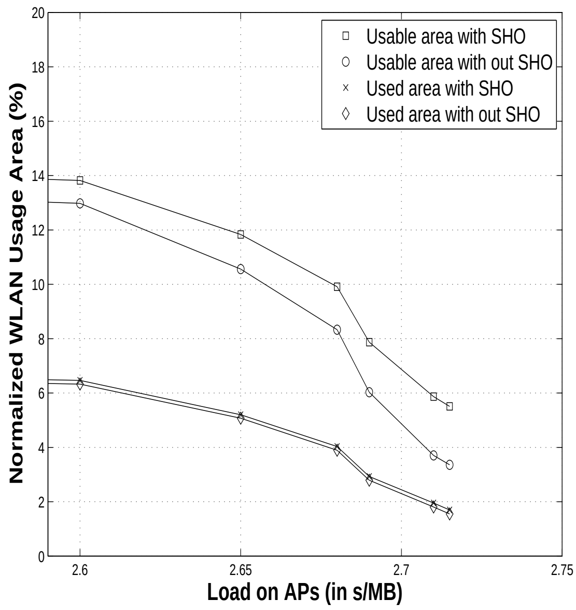


Fig. 7.2: WLAN usable and used area vs load

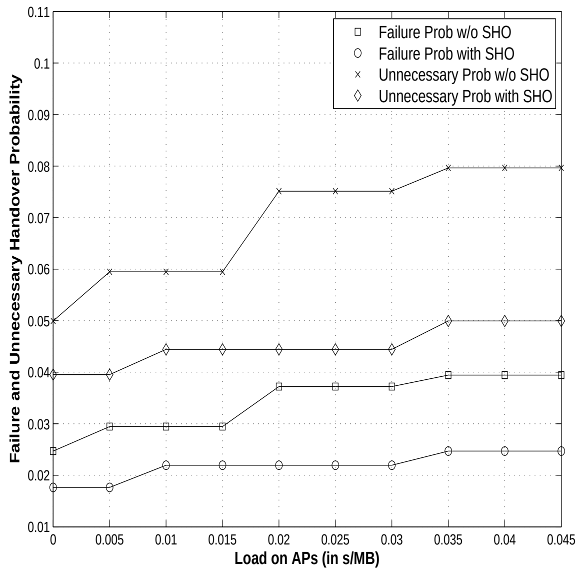


Fig. 7.3: Failure and unnecessary handover probability vs load

area. We observe the similar trend for this approach too. But the magnitude of the usable area obtained by the SINR based approach is found to be slightly lesser than that of the RSS based approach. This is because of the fact that the SINR based approach is concerned with more stricter bounds on the usable area. To avoid repeating the similar curve twice, we omit this figure.

In Figure 7.3, we have shown the impact of load on both handover failure probability and unnecessary handover probability. As described earlier the increase in load causes the usable radius to reduce further. With a smaller usable radius, the MT has a higher probability to go outside the usable region within handover delay interval. Hence an increase in the failure probability is observed. But it is worth noticing that if soft handover is to be introduced, the failure probability reduces drastically. Same holds true for unnecessary handover probability. Also unnecessary handover probability at any given load value is more than handover failure probability. This is due to the fact that the former has a more stringent condition for the MT to stay inside the usable

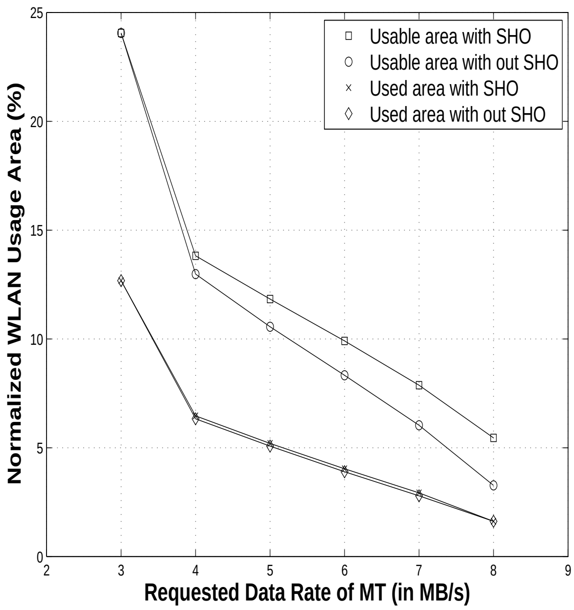


Fig. 7.4: WLAN usable and used area vs data rate

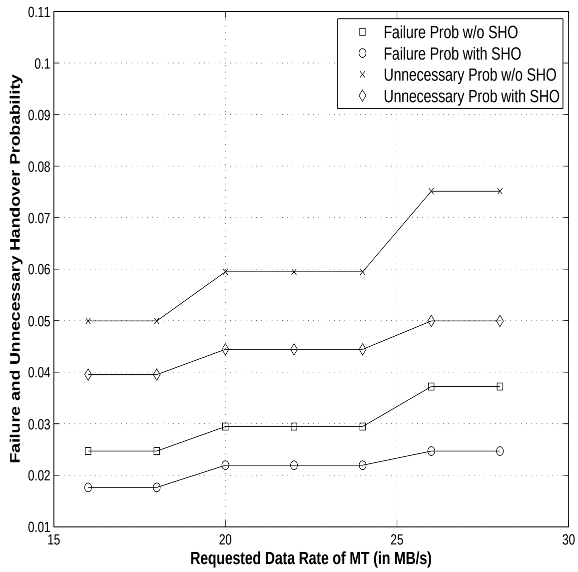


Fig. 7.5: Failure and unnecessary handover probability vs data rate

region twice as long as the later.

## 7.3 Requested Data Rate Versus Metrics

With the increase in the requested data rate of the MT, the WLAN usage area decreases as shown in Figure 7.4. This is due to the fact that with increase in the requested data rate, the required throughput also increases. So the MT should be much nearer to the AP to satisfy its requested data rate thereby decreasing the usable area. Same holds true for the WLAN used area also.

The plot of requested data rate of the MT versus both handover failure probability and unnecessary handover probability (as shown in Figure 7.5) clearly depicts the degrade in the performance due to increase in the data rate. With increase in the data rate, usable region decreases and hence both the probability values increase as described earlier. Again the soft handover between APs enhances the performance significantly.

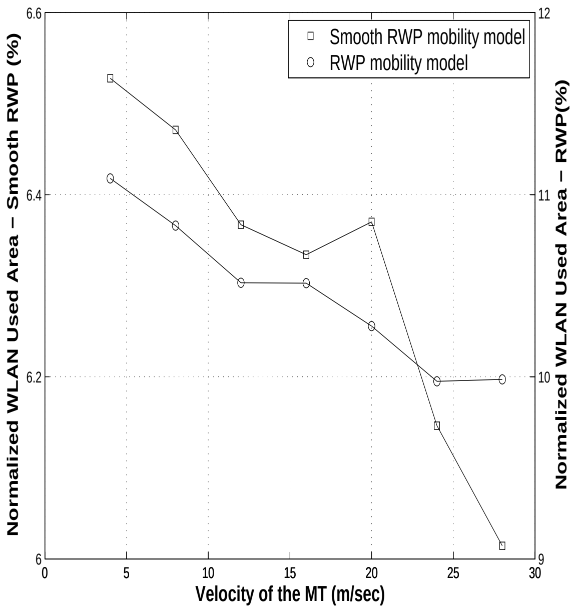


Fig. 7.6: WLAN used area vs velocity

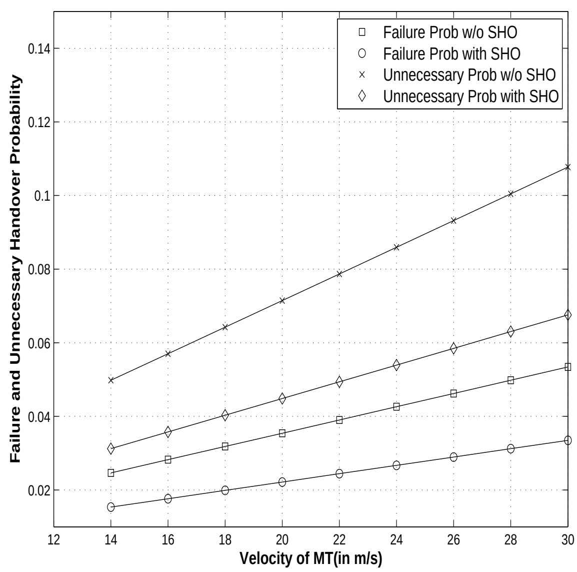


Fig. 7.7: Failure and unnecessary handover probability vs velocity

## 7.4 Velocity Versus Metrics

Consider the plot of the maximum velocity of the moving MT versus WLAN used area for both random waypoint and smooth random waypoint mobility models as shown in Figure 7.6. With the increase in velocity, the time the moving MT will spend inside the WLAN region goes on decreasing thereby decreasing the WLAN used radius of each AP. This decreases WLAN used area. Also it is to be noted that the WLAN used area in case of random waypoint mobility model is far more than that of smooth random waypoint mobility model as the later is a much more realistic version of the former one. As there is a large difference in magnitude of both the plots, in order to show the intended effect, we have plotted the curves along two different axis as shown in Figure 7.6.

Lastly in Figure 7.7 we have shown the plot of velocity of the moving MT versus both handover failure probability and unnecessary handover probability. A higher value of

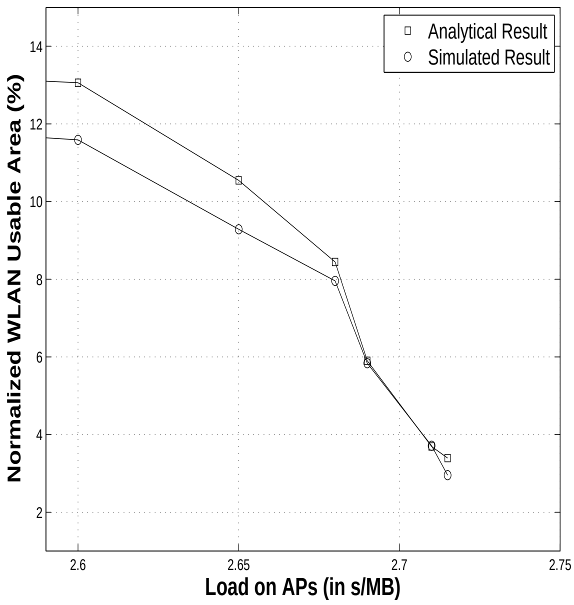


Fig. 7.8: WLAN usable area vs load (Analysis vs Simulation results)

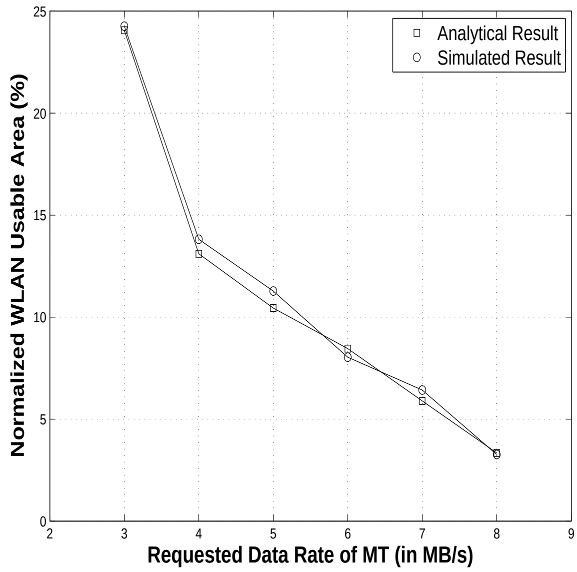


Fig. 7.9: WLAN usable area vs data rate (Analysis vs Simulation results)

velocity (denoted by $v$ in Chapter 5) increases the radius $vt_{ho}$ and hence the failure probability increases. Same holds true for unnecessary handover probability.

## 7.5 Analysis Versus Simulation Results

A comparison between analytical results and the results obtained through computer simulation is shown in Figure 7.8 and Figure 7.9. The results are shown for WLAN usable area versus different parameters. Similar results are obtained for other handover metrics.

# Chapter 8

# Conclusions and Future Work

In this thesis, we have analyzed and derived expressions to evaluate WLAN usable area for multiple AP scenario under load condition. We have also considered the effect of soft handover on various handover performance evaluation metrics. Both load and soft hand over have a strong impact on these metrics. To compute effective throughput of an AP under load we adopted the random polling access method. Other methods such as proportionally fair scheduling can also be considered. To evaluate $r^{used}$ radius for an AP, we have considered all possible velocities and trajectories of the MT moving in both random waypoint mobility model and in smooth random waypoint mobility model. For evaluating handover failure and unnecessary handover probability, random way point mobility model is adopted. Besides these mobility models other mobility models can also be considered for analysis. An analysis with multiple APs and base stations of a heterogeneous network under load condition and vertical soft handover remains author's future work.

# Bibliography


[1] T.M. Ali and M. Saquib, “Analytical framework for WLAN-cellular voice handover evaluation”, *IEEE Trans. on Mobile Computing*, Vol. 12, No. 3, pp. 447-460, March 2013. 3, 7, 25, 30

[2] H. Wang, David I. Laurenson, and J. Hillston, “A General Performance Evaluation Framework for Network Selection Strategies in 3G-WLAN Interworking Networks”, *IEEE Trans. on Mobile Computing*, Vol. 12, No. 5, pp. 447-460, May 2013. 7

[3] A.B.A. Ben Doua, S. Choi, M. S. Alouini and K. A. Qaraqeand, “Adaptive Rake Combining in the Soft Handover Region”, *IEEE Trans. on Wireless Communications*, Vol. 7, No. 12, pp. 5156-5160, Dec 2008. 7

[4] X. Yan, A. Sekercioglu and S. Narayanan, “A survey of vertical handover decision algorithms in Fourth Generation heterogeneous wireless networks”, Computer Networks 54 (2010) 1848-1863. 3, 32

[5] F. Guidolin, I. Pappalardo, A. Zanella and M. Zorzi, “Context-Aware Handover Policies in HetNets”, *IEEE Trans. on Wireless Communications*, Vol. 15, No. 3, pp. 1895-1906, Mar 2016. 7

[6] M. Liu, Z. Li, X. Guo and E. Dutkiewicz, “Performance analysis and optimization of handoff algorithms in heterogeneous wireless networks”, *IEEE Trans. on Mobile Computing*, Vol. 7, No. 7, pp. 846 - 857, 2008. 6

[7] F. Bai and A. Helmy, “A survey of mobility models”, 2004, http://nile.usc.edu/helmy/important/Modified-Chapter1-5-30-04.pdf. vii, 11

[8] Joint Technical Committee of Committee T1 R1P1.4 and TIA TR46.3.3/TR45.4.4 on Wireless Access, "Draft final report on *RF* characterization" Paper No. JTC(AIR)/94.01.17-238R4, January 17, 1994. 12

[9] S. Mohanty and I. F. Akyildiz, " A cross-layer (layer 2 + 3) handoff management protocol for next-generation wireless systems", *IEEE Trans. on Mobile Computing*, Vol. 5, No. 10, pp. 1347-1360, 2006. 6

[10] K. Yang, I. Gondal, B. Qiu and L.S. Dooley, " Combined SINR based vertical handoff algorithm for next generation heterogeneous wireless networks", *IEEE Global Telecommunications Conference (GLOBECOM 07)*, pp. 4483-4487, November 2007. 6

[11] A.H. Zahran, B. Liang and A. Saleh, " Signal threshold adaptation for vertical handoff in heterogeneous wireless networks", *Mobile Networks and Applications*, pp. 625-640, 2006. 6

[12] F. Zhu and J. McNair, " Optimizations for vertical handoff decision algorithms", *IEEE Wireless Communications and Networking Conference (WCNC 04)*, pp. 867-872, March 2004. 6

[13] M. Ghaderi and R. Boutaba, "Call Admission Control for Voice/Data Integration in Broadband Wireless Networks", *IEEE Trans. on Mobile Computing*, Vol. 3, No. 5, pp. 193-207, March 2006. 7

[14] S.A. Sharna and M.M. Murshed, "Performance analysis of vertical handoff algorithms with QoS parameter differentiation", in *Proc. of the 12th IEEE HPCC*, pp. 623 - 628, September 2010. 7

[15] Y. Fangand and I. Chlamtac, "Analytical Generalized Results for Handoff Probability in Wireless Networks", *IEEE Trans. on Communications*, Vol. 50, No. 3, pp. 396-399, March 2002. 7

[16] E. Stevens-Navarro, Y. Lin and V.W. Wong, "An MDP-Based Vertical Handoff Decision Algorithm for Heterogeneous Wireless Networks", *IEEE Trans. on Vehicular Technology*, Vol. 57, No. 2, pp. 1243-1254, Mar. 2008. 6

[17] X. Lin, R. K. Ganti, P. J. Fleming and J. G. Andrews, "Towards Understanding the Fundamentals of Mobility in Cellular Networks", *IEEE Trans. on Wireless Communications*, Vol. 12, No. 4, pp. 1686-1698, Apr 2013. 24

[18] S. Tong, L. Min and L. Zhongcheng, "A performance evaluation model for RSS-based vertical handoff algorithms", in *Proc. of IEEE Symposium on Computers and Communications (ISCC)*, pp. 271-276, 2009. 7

[19] Y. Sun, C. Liu, P. Yang, and X. Wen, "A smart vertical handoff decision algorithm based on queuing theory", in *Proc. of the 16th International Conference on Advanced Communication Technology (ICACT)*, pp. 1217-1222, February 2014. 6

[20] C. Makaya and S. Pierre "An Analytical Framework for Performance Evaluation of IPv6-Based Mobility Management Protocols", *IEEE Trans. on Wireless Communications*, Vol. 7, No. 3, pp. 972-983, Mar 2008. 7

[21] S. Maaloul, M. Afif, and S. Tabbane, "An efficient handover decision making for heterogeneous wireless connectivity management", in *Proc. of the International Conference on Software, Telecommunications and Computer Networks*, pp. 1-8, September 2013. 6

[22] Y. Feng, L. Xie, H. Chen, and K. Wang, "A low-complexity fuzzy-logic-control-based vertical handoff decision algorithm with rough set theory", in *Proc. of*

*the International Conference on Wireless Communications and Signal Processing (WCSP)*, pp. 1-6, October 2013. 6

[23] M. Barooah, S. Ahuja, S. Chakraborty and S. Nandi, 'TCP performance for WLAN-GPRS handover in an intermediate switching network based framework", in *Proc. of 5th IEEE ANTS*, pp. 1-6, 2011. 6

[24] M. Lott, M. Siebert, S. Bonjour, D. von Hugo, and M. Weckerle , "Interworking of WLAN and 3G systems", *IEE Proceedings-Communications*, Vol. 151, No. 5, pp. 507-513, October 2004. 6

[25] R. Mardeni and K. F. Kwan , "Optimization of hata propagation prediction model in suburban area in Malaysia", *Progress In Electromagnetic Research*, Vol. 13, pp. 91-106, 2010. 12

[26] A. Kumar and V. Kumar, "Optimal association of stations and APs in an IEEE 802.11 WLAN", in *Proc. of the National Communications Conference (NCC)* January 2005. 10

[27] Y. Fukuda and Y. Oie, "Decentralized access point selection architecture for wireless LANs: Deployability and robustness", in *Proc. of VTC Fall*, pp. 1103-1107, 2004. 10

[28] M.T. Lee, L.T. Lai and D. Lai, "Enhanced algorithm for initial ap selection and roaming", U.S. Patent 0039817, February 2004. 10

[29] H. Velayos, V. Aleo, and G. Karlsson, "Load balancing in overlapping wireless LAN cells", in *Proc. of the IEEE ICC*, pp. 3833-3836, September 2004. 10

[30] L.C. Paul , "Handoff / Handover Mechanism for Mobility Improvement in Wireless Communication", in *Proc. of the Global Journal of Researches in Electrical and Electronics Engineering*, vol 13, 2013. vii, 2

[31] S. Raychaudhuri, "Introduction to monte carlo simulation", in *Proc. of the Winter Simulation Conference*, pp. 91-100, 2008. 13

[32] C. Bettstetter, "Smooth is better than sharp: a random mobility model for simulation of wireless networks", in *Proc. of the 4th ACM International Workshop on Modeling,Analysis and Simulation of Wireless and Mobile Systems*, pp. 19-27, 2001. 26, 41

[33] K. Pahlavan and P. Krishnamurthy, "Principles of wireless access and localization", *John Wiley and Sons*, ISBN: 978-0-470-69708-5, 2013. 15, 41

[34] M. Mouton, G. Castignani, R. Frank, L. Codeca, and T. Engel, "on the evaluation of make-before-break handovers in urban WiFi networks for moving vehicles", in *Proc. of the 10th International Conference on Wireless On-demand Network Systems and Services*, 2013. 7

[35] J. Petajajarvi and H. Karvonen, "Soft handover method for mobile wireless sensor networks based on 6LoWPAN", in *Proc. of the IEEE DCOSS*, pp. 1-6, 2011. 6

[36] Z. Zinonos and V. Vassiliou, "S-ginmob: Soft-handoff solution for mobile users in industrial environments", in *Proc. of the IEEE DCOSS*, pp. 1-6, 2011. 6

[37] E. Ivov and T. Noel, "Soft handovers over 802.11b with multiple interfaces", in *Proc. of the 2nd International Symposium on Wireless Communication Systems*, pp. 549-554, September 2005. 7

[38] J. Broch, D.A. Maltz, D.B. Johnson, Y.C. Hu and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols", in *Proc. of ACM MOBICOM*, pp. 85-97, 1998. 24

[39] M.Sharir, "Intersection and closest-pair problems for a set of planar discs", *SIAM Journal of Computing*, pp. 448-468, 1985. 12

[40] Paul G. Spirakis, “Very fast algorithms for the area of the union of many circles”, Rep. 98, Dept. Computer Science, Courant Institute, New York University, 1983. 13

[41] X. Yan, N. Mani and Y.A. Sekercioglu, “A traveling distance prediction based method to minimize unnecessary handovers from cellular networks to WLANs”, IEEE Communications Letters 12 (1), pp. 14-16, 2008. 23, 40

[42] M. P. Fewell, “Area of common overlap of three circles”, Technical Note DSTO-TN-0722, Defence Science and Technology Organization, Edinburgh, Australia, 2006. 13, 34