HANDOFF DECISION ALGORITHMS FOR RAPIDLY DEPLOYABLE MOBILE INFRASTRUCTURE COMMUNICATION NETWORKS

by

Tolga Önel

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APPROVED BY:

Assoc. Prof. Cem Ersoy..
(Thesis Supervisor)

Dr. Erdal Çayırcı...
(Thesis Co-supervisor)

Assoc. Prof. H. Levent Akın..

Prof. M. Ufuk Çağlayan..

Assoc. Prof. Günhan Dündar...

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ABSTRACT

HANDOFF DECISION ALGORITHMS FOR RAPIDLY DEPLOYABLE MOBILE INFRASTRUCTURE COMMUNICATION NETWORKS

Mobile communication systems should use limited resources in an efficient and convenient manner. One way of achieving this is to use smaller cells in the expense of corresponding handoff and administration overhead.

Several algorithms are proposed to decide whether a handoff is necessary for a mobile or not. These algorithms differ according to the metrics used, where the metrics are monitored, and how these metrics are used.

Some applications like military tactical communication and disaster area communication infrastructure deployment require rapid deployment of the mobile infrastructure. To satisfy rapid deployment and survivability requirement, architectures with mobile cell-managing units are employed.

For the systems having a mobile infrastructure, handoff requires special treatment. We propose a handoff decision algorithm based on fuzzy inference systems. We use simulation to evaluate the performance of the proposed algorithm. The evaluated performance of the algorithm shows that our algorithm performs the best among the conventional received signal strength based handoff decision algorithms.

With slight modifications, our proposed handoff decision algorithm is applicable to the systems having immobile infrastructure.

ÖZET

SÜRATLE YERLEŞTİRİLEBİLEN GEZGİN ALTYAPILI İLETİŞİM AĞLARINDA ELDEĞİŞTİRME ALGORİTMALARI

Gezgin iletişim sistemleri ortamdaki sınırlı kaynakları verimli ve uygun bir biçimde kullanmalıdırlar. Bunu gerçekleştirmenin bir yolu, daha küçük hücreler kullanmaktır. Nevarki küçük hücreler eldeğiştirme ve ağ yönetim işlemleri açısından sisteme extra yük getirirler.

Gezgin için eldeğiştirme işleminin gerekliliğine karar vermek üzere önerilmiş birçok algoritma mevcuttur. Bu algoritmalar, kullandıkları kıstaslara, bu kıstaların nerede ölçüldüklerine ve nasıl değerlendirildiklerine göre farklılıklar gösterirler.

Askeri taktik muhabere sistemleri ve afet bölgesinde iletişim gibi bazı uygulamalar, gezgin iletişim sistemi altyapısının hızlı ve idame edilebilir bir şekilde yerleştirilmesine ihtiyaç duyarlar. Bunu gerçekleştirmek için gezgin hücre yöneticilerinin kullanıldığı sistemler mevcuttur.

Gezgin altyapılı sistemlerde eldeğiştirme işlemi özel bir dikkat ister. Bu tezde önerilen eldeğiştirme algoritması bulanık sonuç çıkarma sistemlerine dayanmaktadır. Sistem başarım değerlendirmesinde kullanılan benzetim yöntemi, önerilen eldeğiştirme algoritmasının klasik sinyal tabanlı eldeğistirme algoritmalarından daha iyi oldugunu göstermektedir.

Önerilen algoritma, ufak uyarlamalarla sabit altyapılı sistemlere de uygulanabilir.

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AP_C	Currently serving access point
AP_N	Candidate access point
d	Distance between the mobile and the access point
d_0	Fresnel zone breakpoint
E_b/N_0	Energy required per bit to noise density ratio
F	Fuzzy set
H	Received signal strength hysteresis value
h_1	Transmitter antenna height
h_2	Receiver antenna height
H	The fuzzy set '*high*'
I/S	Interference to signal ratio
L	The fuzzy set '*low*'
L_p	Path loss
M	The fuzzy set '*Medium*'
N	Number of users related with an access point
N_s	Number of users per sector
P_k	Parameter of the Rayleight density function
PV_c	Pattern vector for current access point
PV_F	Fuzzy pattern vector
PV_N	Pattern vector for candidate access point
R	Information bit rate
r_k	Envelope of the received signal strength
r_m	Distance of mobile from its cell site
r_o	Distance of an interfering mobile to the interfered mobile's cell site
S	Signal power
SCU	Used soft capacity of an access point
SoA	Set of access points
T	Received signal strength threshold value
U	Universe of discourse
V	Speed

W	Carrier bandwidth
W/R	Processing gain

α	Voice activity factor
ΔV	Relative speed of a mobile to an access point
$\Delta\theta$	Relative direction of a mobile to an access point
η	Background noise
λ	Wavelength of the transmitted signal
μ	Membership value
σ	Standard deviation
ξ	A gaussian random variable

AP	Access point
BER	Bit error rate
CDMA	Code division multiple access
FDMA	Frequency division multiple access
FIS	Fuzzy Inference System
GPS	Global positioning system
GSM	Global system for mobiles
HHO	Hard handoff
IS	Interim standard
JTLS	Joint theater level simulation
LCR	Level crossing rates
MAHO	Mobile assisted handoff
MCHO	Mobile controlled handoff
MCHOA	Multi-criteria handoff decision algorithm
MCSHO	Multiple channel soft handoff
ML	Maximum likelihood
MMSE	Minimum mean square error
MPR	Man packed radio
MPRT	Man packed radio tier
MS	Mobile subsystem

NCHO	Network controlled handoff
QoS	Quality of service
RAP	Radio access point
RAPT	Radio access point tier
RMS	Root mean square
RSS	Received signal strength
SATT	Satellite tier
SCSHO	Single channel soft handoff
SHO	Soft handoff
SHW	Soft handoff window
SIR	Signal to interference ratio
SNR	Signal to noise ratio
TDMA	Time division multiple access
UAV	Unmanned aerial vehicle
UAVT	Unmanned aerial vehicle tier
VCL	Virtual cell layout
WAS	Wide area subsystem
ZCR	Zero crossing rates
ZSR	Zone selection rate

1. INTRODUCTION

The next generation tactical communications systems should provide battle forces an efficient, robust, flexible, and tailorable network that can convey multimedia traffic. In [1], a novel resource management technique, namely virtual cell layout (VCL) is proposed for tactical mobile communications systems. VCL approach assigns radio resources to geographic locations to satisfy rapid deployment, survivability, flexibility, and tailorability requirements of the next generation tactical communications systems. The system proposed in [1] has a mobile infrastructure, and we can expect that the mobiles move together with their base transceivers, because both the base transceivers and the mobiles owned by the same unit are deployed together. If a mobile executes a handoff solely for detection of a stronger emission from another base transceiver, it may need another handoff to its former base transceiver soon.

Many handoff algorithms proposed in the literature are classified according to the metrics used to decide whether a handoff is necessary for a mobile or not, where these metrics are monitored, and how these metrics are processed. Some of the metrics proposed are signal strength, distance, signal to noise ratio, bit error rate, traffic load, word error indicator, quality indicator, and some combination of these [2]. These metrics can be measured and processed on the network entity or on the mobile. There are several handoff decision algorithms proposed that employs tools of artificial intelligence like fuzzy logic systems, neural networks, and pattern recognition algorithms to process the collected metrics [3].

In the VCL proposal [1], utilized handoff decision algorithm is based on the received signal strength measurements from the base transceivers in the vicinity. To keep the number of unnecessary handoffs at minimum, mobiles do not hand off to another base transceiver while the received signal strength from the current base transceiver adequate to carry on the communication. However, this algorithm results in inefficient use of network resources due to increasing global interference level.

We propose a handoff decision algorithm based on fuzzy inference systems. In our proposed handoff decision algorithm, measured decision metrics are received signal strengths from the current and candidate base transceivers, total and used soft capacities of the base transceivers, relative directions and speeds of the base transceivers. Soft capacity is a function of the interference level that is affecting to the base transceiver. Output of our utilized fuzzy inference system is the membership value of a mobile to the current and candidate access points, which is a real number between one and nine. We introduced membership value threshold to trigger the handoff decision algorithm, i.e., the mobile does not think handing off while its membership value to its current base transceiver is above a predetermined threshold. If a handoff is necessary, base transceiver with the mobile's highest membership value is the target for handoff. We compare our algorithm with the received signal strength based handoff decision algorithms. Our tests for the studied cases have shown that setting the membership value threshold to the highest achieves minimum ratio of blocked calls due to lack of network resources to total calls. Moreover setting the membership value threshold to one achieves the minimum number of handoffs. Where the former case keeps the number of handoffs in an acceptable level, the latter case keeps the ratio of blocked calls to total calls in an acceptable level. So our proposed handoff decision algorithm seems like an optimization of two conflicting criteria, the number of handoffs and the ratio of blocked calls due to lack of network resources to total calls.

1.1. Contribution of the Thesis

In this thesis, we compare handoff decision algorithms based on received signal strength with different threshold and hysteresis parameters. We formalize the handoff algorithms for the components of the Virtual Cell Layout (VCL) architecture. We also propose a handoff decision stage algorithm based on fuzzy inference systems for mobile infrastructure architectures. With slight modifications, the algorithm can be used for systems having an immobile infrastructure. We use simulation to evaluate the performance of the proposed algorithm Our proposed algorithm performs better in terms of blocked calls due to lack of network resources, i.e. better grade of service, and total number of handoffs.

1.2. Structure of the Thesis

In the next chapter, foundations of handoff problem in mobile communication networks and fuzzy logic systems are given.

An example mobile infrastructure architecture proposed in [4] is introduced in Chapter 3. The Handoff types and algorithms for Virtual Cell Layout (VCL) is examined in detail in this chapter.

The proposed handoff decision algorithm based on fuzzy inference systems is described in Chapter 4.

Chapter 5 provides comparison of the various handoff algorithms for the VCL architecture and comparison of the proposed handoff decision algorithm with the conventional ones according to the performance metrics of blocked calls due to lack of network resources and total number of handoffs.

Finally, we conclude in Chapter 6, and discuss our future works.

2. HANDOFF AND FUZZY LOGIC SYSTEMS FOUNDATIONS

Increasing number of mobile subscribers requires more efficient use of available limited frequency band. One way of achieving this is to use smaller cells. This increases the spectrum efficiency at the expense of handoff and corresponding administration overhead. Smaller cells also provide us low-power hand held user devices.

Cellular systems must have the ability to maintain a call even while a mobile subscriber moves throughout a cellular service area [2]. This is accomplished by transferring the mobile station from one base station or channel to another when the quality of current channel is not adequate. The channel change due to handoff occurs throughout a frequency band for frequency division multiple access (FDMA) systems, and codeword for code division multiple access (CDMA) systems [3] or combination of these in hybrid systems.

2.1. Introduction to Handoff Problem

Causes of the handoff are mostly radio link related, network management related, or service options related. Received signal strength, signal to interference ratio, and system related constraints like the synchronization requirement of time division multiple access systems constitute the radio link related causes of the handoff, which is the most common reason.

A variety of parameters have been suggested for evaluating the link quality to decide when a handoff should be carried out. Some of these are:

- Bit error rate (BER)
- Signal to noise ratio (SNR)
- Distance
- Traffic load
- Signal Strength
- Word Error Indicator

- Quality Indicator
- Combinations of these.

A common scenario used for comparing handoff algorithms is the canonical scenario [5] in which one mobile goes from one base station towards another as in Figure 2.1. Optimally, we expect the mobile to handoff from base 1 to base 2 in the middle of the route, point A in Figure 2.1 This can be decided when the signal strength, received from base 2, exceeds the signal strength received from base 1 when traveling from base 1 through base 2. Signal perceived from a base station degrades while mobile goes away from that base station. However this degradation is a random process due to uncertainties in the propagation environment. Around point A received signal strengths from base 1 and base 2 oscillates and mobile handoffs several times between base 1 and base 2. This is called the ping-pong effect. Simple handoff algorithms, for example that considers only the received signal strength, affected by the ping-pong effect that is a mobile communicating throughout two base stations back and forth. This is called a mini-loop if only two base-stations involved also the loop may contain more than one base stations which is called a macro-loop. There are several techniques proposed to prevent the ping-pong effect. For example, we can introduce a threshold level to the received signal strength algorithm. That is a mobile does not think handing off as long as the received signal strength from the currently serving base station does not drop below the predetermined threshold level. That means handoff to the new base station is executed if

$$(RSScurrent < threshold) \text{ and } (RSSnew > RSScurrent) \tag{2.1}$$

where,

RSScurrent is the received signal strength from the registered base station,
RSSnew is the received signal strength from the candidate base station to handoff,
Threshold is the signal threshold for triggering the handoff decision algorithm.

In Figure 2.1, if we use the received signal strength based handoff algorithm with T_3 dB threshold, mobile going from base 1 to base 2 hands off from base 1 to base 2 at point *'D'*. If we use T_1 dB threshold then the handoff point is *'A'* where the received signal strength from base 2 exceeds received signal strength from base 1. Similarly for T_2 dB threshold handoff point is *'B'*.

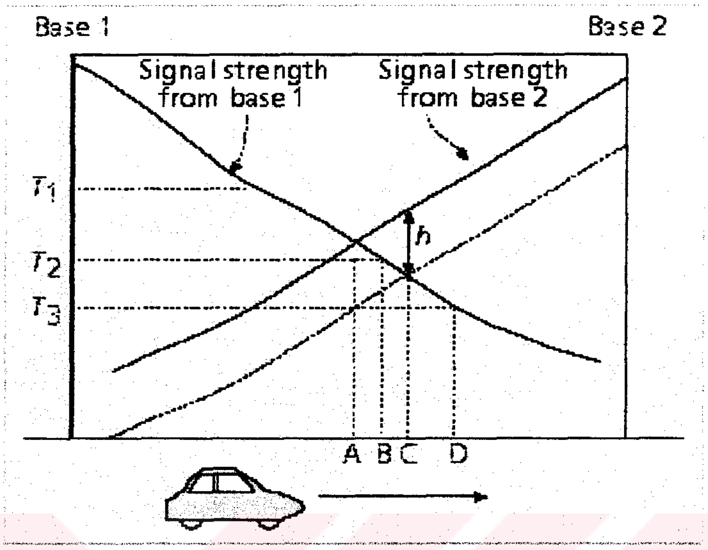


Figure 2.1. The canonical scenario [5]

Another technique is to introduce hysteresis. That is a mobile does not think handing off to another base station while the received signal strength from the candidate base station is not better an amount of predetermined hysteresis level than the received signal strength of the currently serving base station. This can be thought as subtracting the hysteresis value from the candidate base stations received signal level and comparing the resulting signal strengths with the currently serving base stations signal strength level. That means the call is handed off to the new base station if

$$(RSScurrent < RSSnew\text{-}hysteresis) \tag{2.2}$$

In Figure 2.1, if we use the received signal strength based handoff decision algorithm with h dB hysteresis, mobile hands off from base 1 to base 2 at point *'C'*, where received signal strength from base 2 is better than the received signal strength from base 1 an amount of h dB.

Either introducing hysteresis or threshold reduces the ping-pong effect but introduces a delay to handoff, i.e., handoff is done later than it is expected. Effects of delaying handoff are increased interference, low communication quality (QoS), and possibly dropped calls. Delayed handoff means mobile has entered to a new base stations service area (cell) but still communicating through its old base station and channels. This results the mobile to transmit with a higher power to access the serving far away base station because of the power control mechanism of CDMA systems. Base stations using the same channel in the vicinity are affected from that signal. So, the result is increased co-channel interference. Also delayed handoff causes mobile to use the low quality channel while a better one is available. Hence, QoS drops and continuing to try communicating through a low quality link may cause the call to drop eventually if the signal level drops below a certain level.

There are studies that have optimized signal-strength based handoff algorithms by minimizing two conflicting design criteria. The handoff delay and the mean number of handoffs between base stations [2]. As a result in design of handoff algorithms there is an inherent trade off in timeliness and accuracy.

Another method for avoiding to relate the handoff decision to a sudden dropped or increased signal, due to small-scale fading characteristics of the received signal, is to average the received signal in a temporal or spatial window. Shape and the size of this sampling window is another design parameter for handoff algorithms.

Another technique to reduce ping-pong affect is to employ “dwell timer” that is if the handoff condition remains satisfied for a predetermined time, perform handoff otherwise do not perform a handoff.

When a mobile moves throughout the coverage area of a new cell if no available channel found in the new cell this results with the forced termination of the call. Terminating an ongoing call irritates people much more than inability to create a new call. To ease the problem every cell reserves some of its communication channels for handoffed mobiles. These reserved channels are called guard channels and the number of guard channels in a cell is a cellular network design parameter. Trade off in the number of guard channels is between forced termination probability and new call blocking probability. Higher number of guard channels means lower forced termination probability and higher new call blocking probability and lower number of guard channels means higher forced termination probability and lower new call blocking probability. In [6] a call admission control approach based on reinforcement learning for improving the quality of service in cellular mobile multimedia networks, while prioritizing handoff call requests over new call requests is proposed. In the proposed scheme in [7] the handoff of voice services adopts the scheme of guard channels and the handoff of data services employs the scheme of queuing model. Overlay macro-cell channels may serve as guard channels to low mobility users. Hierarchical cellular systems provide efficient use of available channels, load balancing and small number of handoffs since low speed users associated with micro-cells and high-speed users are associated with overlay macro-cells. In [8] a hierarchical cellular system with an underflow schema that permits overflow calls, which are produced by low mobility users, to return from macro-cell to micro-cell when a communication channel in the micro-cell gets available. This algorithm prevents inflation of low mobility users in the macro-cell.

2.2. Handoff Control

Handoff decision algorithms may be run on network entity or on mobile. Former is called Network Controlled Handoff (NCHO) where the later is called Mobile Controlled Handoff (MCHO). For NCHO network entity monitors the parameters of the handoff decision for all mobiles related with it and decides if handoff for a mobile is necessary or not. Similarly for MCHO, each mobile monitor the parameters of the handoff decision and decide if a handoff is necessary or not. Another handoff control mechanism is that mobile monitors the parameters and reports them to the network entity and network entity decides if a handoff for that mobile is necessary or not. This mechanism is called Mobile Assisted Handoff (MAHO).

For NCHO, when network decides to handoff a mobile, it blanks the data or voice channel and sends the handoff command. Sometimes, the network sets up a bridge connection between old and new base station and thus minimizes the duration of handoff.

For MCHO, mobile host has the complete control over handoff procedure. The mobile host does not have information about the signal quality of other users and yet, handoff must not cause interference to other users. The mobile host measures the signal strengths from surrounding base stations and interference levels on all channels [3]. Mobile host requests a channel from the target base station with the lowest interference.

NCHO has the most delay in handoff (i.e., the time required to execute a handoff request) where NCHO has the most measurement information to decide a handoff. MAHO is middle and MCHO is the fastest when handoff delay is concerned but has the least measurement information, to provide a manageable amount of data, about handoff decision parameters. According to [9] the overall delay can be approximately five to ten seconds for NCHO, one second for MAHO, and 100 ms for MCHO.

2.3. Handoff Stages

Handoff is performed in three stages; Decision stage, planning stage, and execution stage [10].

In the decision stage, the handoff decision is made in the network or at the mobile, according to some metrics like RSS, BER, SNR, Cell traffic. A handoff decision algorithm like Received Signal Strength, RSS with threshold, RSS with hysteresis, RSS with threshold and hysteresis, velocity adaptive handoff algorithm, multi-criteria handoff algorithm, or pattern recognition based handoff algorithm is employed in this stage. These algorithms will be discussed in Section 2.4 of this thesis.

If a handoff is decided, then the next stage is the planning stage where the appropriate channel, which is free and has least interference, from the candidate base station is found and authentication protocols employed if necessary.

Now handoff can be executed in execution stage where the mobile host dissociates from old serving base station and re-associates to the new candidate base station.

2.4. Handoff Decision Algorithms

Received Signal Strength (RSS) based handoff algorithm associates mobile host to the base station which has the strongest perceived signal strength at the mobile host side. As apparent this algorithm is vulnerable to ping-pong effect. To overcome this difficulty we introduce threshold to the Received Signal Strength based algorithm. This is called Absolute Signal Strength algorithm. Or we introduce hysteresis to RSS algorithm this is called Relative Signal Strength algorithm. Introducing both hysteresis and threshold is called combined absolute and relative signal strength algorithm. Mentioned algorithms were signal strength based algorithms. Distance based algorithms relate the mobile with closest base station. The relative distance measurements can be obtained by comparing propagation delay times. Signal to interference ratio (SIR) based handoff algorithms consider communication quality. When another base station or another channel of the serving base station provides better SIR, a handoff to that base station or channel is considered. The former is called inter-cell handoff where the latter is called intra-cell handoff. Velocity adaptive handoff algorithms consider mobiles with different velocities i.e. handoff needs of fast moving mobiles should be determined immediately. This can be achieved by adjusting the effective length of the averaging window [2]. In direction biased algorithms, handoffs to the base stations towards which the mobile is moving are encouraged, while handoffs to the base stations from which the mobile is receding are discouraged. In pre-selection handoff algorithm mobile hands off to the base station towards which the mobile is moving even though measured handoff decision metrics of that base station is not the best ones, thinking that these metrics will improve in the near future. Minimum power algorithms minimizes the uplink (mobile to base) transmit power by searching for a suitable combination of base station and a channel.

For multi-criteria handoff decision algorithms, pattern recognition based handoff decision algorithms have been proposed [3,11,12]. Fuzzy logic systems and neural network classifiers are good candidates for pattern classifiers due to their non-linearity and generalization capability. When employing pattern recognition based algorithms we have the overhead of obtaining the training data and pre-training the system. But when the system is trained we have the opportunity to employ multi-criteria algorithms and optimizing the handoff decision with conflicting criteria (i.e. handoff delay and number of handoffs).

2.5. Handoff Planning

After a mobile or network entity decides that a handoff is needed for that mobile, handoff planning process begins to find an appropriate candidate communication channel. Handoff planning operations change according to whether handoff is controlled by mobile or by network and the level of handoff. Handoff may be within the channels of an access point (intra-access point handoff) or between access points (inter-access point handoff) or between access point control units (inter-access point control unit handoff) while an access point control unit may have more than one access points that it controls. Figure 2.2 shows a mobile assisted inter-access point handoff message flow to give an idea about handoff planning message traffic.

Figure 2.2 is also message flow for GSM (Global System for Mobiles) system. Notice that message 6 is received by the mobile from an unreliable link of the old base station. Failure in receiving message 6 results with the failure in the handoff. In Mobile controlled handoff, Mobile sends the handoff-required message by itself to the new access point (Message corresponding to message 2 in MAHO). And the handoff command message (Message corresponding to message 6 in MAHO) comes from new more reliable link.

2.6. Handoff Execution

There are two approaches depending on if the old connection is broken before establishing the new one or not. Former is called "break before make" approach also named as hard handoff (HHO) where the later is called "make before break" approach also named as soft handoff (SHO).

In soft handoff mobile uses the same frequency communication data channel from different base stations. In CDMA systems neighboring cells may use the same frequency data channel. So SHO may be employed.

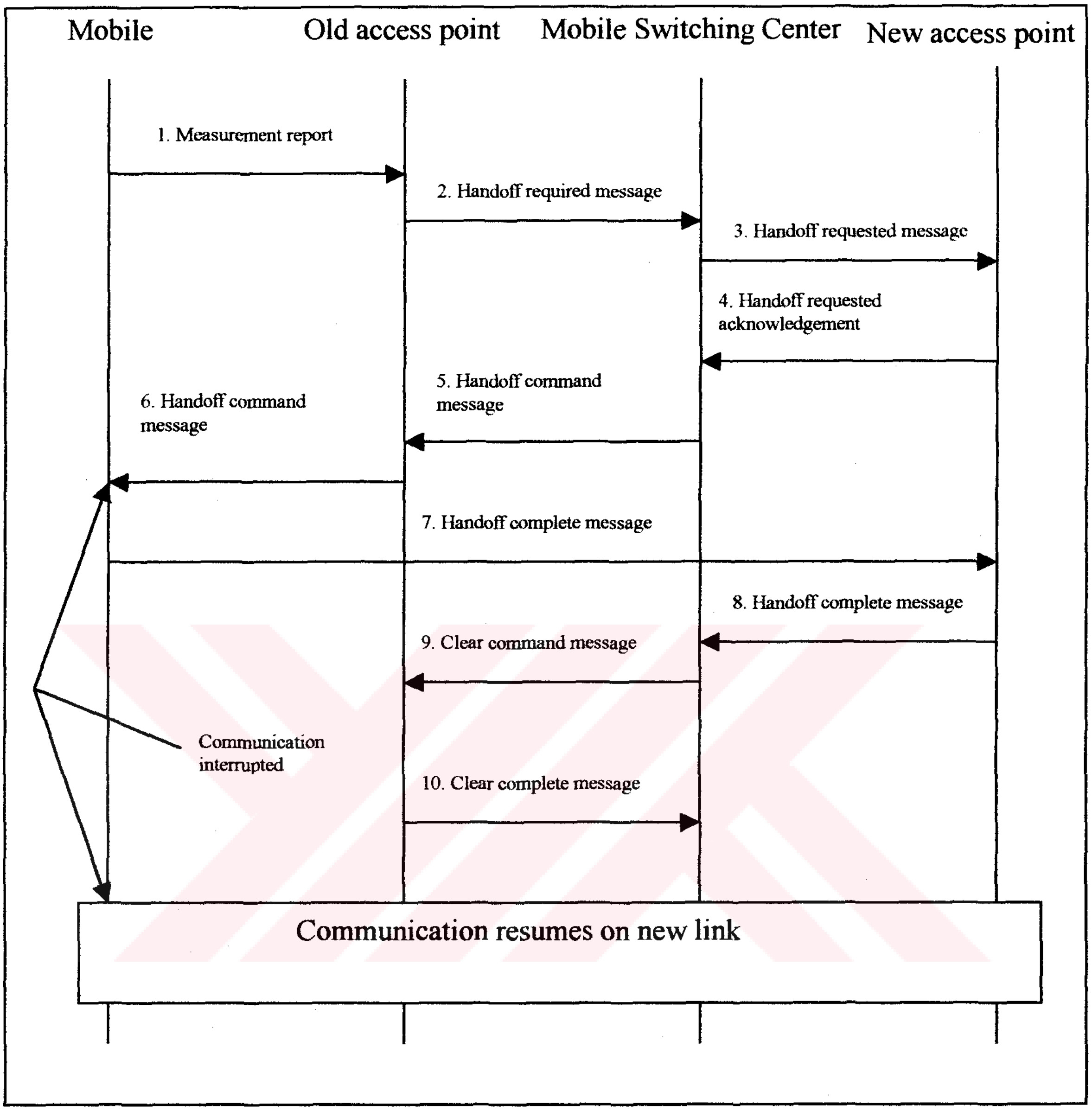


Figure 2.2. Inter access point handoff message flow for mobile assisted handoff [13]

Soft handoff can be thought as the membership to an active set of base stations. Base stations that have the channel quality above an add threshold are added to the active list. Active list may contain more than one base station for soft handoff. Hard handoff can be thought of as allowing at most one base station in the active list. If a base station in the active list drops below a drop threshold and keeps dropped for a predetermined dwell time that base station is removed from the active list. Difference between add and drop threshold is defined as soft handoff window (SHW) [14]. SHW is the design parameter of the soft handoff systems. In [15] soft handoff algorithms based on Fuzzy Inference

Systems (FIS) aim to increase the values of drop threshold and SHW, and add threshold in order to release the traffic channel at high traffic loads for increasing the carried traffic. In [16] adaptive SHO threshold using the classic gradient descent method is proposed. Some systems allow soft handoff only in a soft handoff region and the ratio of soft handoff region area to cell area adjusted by changing SHW. IS-95 includes other sets named candidate set, neighbor set and remaining set [14]. Mobile uses the channels in the active list simultaneously, that is communicates through all of them, Candidate set contains channels that are as good as the ones in the active list and these channels are candidates for the active list when needed, neighbor set includes channels which do not meet the criteria to participate in the active or candidate set but reasonably strong. Remaining set contains all the others.

Soft handoff employs a technique called macroscopic diversity in which different base stations receives transmissions from a mobile station to obtain a good quality communication link. Macroscopic diversity is based on the principle of diversity combining that assumes different base-stations transmit and receive the same call with uncorrelated signal paths [3]. Some diversity combining techniques include selection diversity in which the signal with the strongest SNR is selected, maximum ratio combining in which the co-phased signals are added with a weight factor according to their SNR, and equal gain combining in which a summation of the co-phased signals at the receiver is made with equal weighting factor.

The mobile hosts employing diversity combining must decode the signals from all base stations, which may be using the same or different channels. If the same channels are used this is called single channel SHO (SCSHO) and if different channels are used this is called multiple channel SHO (MCSHO). In general signal quality will be better for MCSHO than SCSHO since the receiver has more degrees of freedom. However, at high traffic intensities, the MCSHO schema may not be feasible due to the unavailability of channels [3].

While hard handoff employs hysteresis or threshold to avoid micro or macro loops, Soft handoff employs the active list concept. So in hard handoff there is a handoff decision delay depending on the hysteresis or threshold value. This increases the interference, especially in power-controlled systems, and consequently reduces the system capacity. In soft handoff, there is no hysteresis or threshold so the result is reduction in uplink interference. However, the active list may contain more than one channel, which may belong to the different base stations. So, one mobile may occupy more than one channel. This results in an increase in downlink interference since the same data is transmitted by more than one base stations.

Soft handoff requires tight synchronization between all base stations in the network to maintain data synchronization after handoff.

Unlike hard handoff, soft handoff is imperceptible by the user in the expense of synchronization overhead since no communication break is present.

There are techniques for mobile to receive the packets in the correct order and only one copy. These are; marking technique, last send technique, last received technique [17].

2.7. Propagation Model

In wireless communication systems, signals travel through air to reach their destination. The mobile hosts may use the air interface to access a wired communication infrastructure. Likewise the communication network must use the air interface to access the mobile host. For every case, the air interface is the vital component of wireless communication systems. In wireless communication environments, radio waves propagate through various mechanisms such as reflection, diffraction and scattering. A propagation model predicts the strength of the radio signal and its variability at a given distance from the transmitter. The radio signals traveling in the air are affected by three main components.

The first component is related to the distance between the transmitter and the receiver. The distance and the received signal strength are inversely proportional. In free space, path loss formula is [18,19]:

$$L_p = 10\log\left[\left(\frac{4\pi d}{\lambda}\right)^2\right] \tag{2.3}$$

where,

d is the distance from the transmitter,

λ is the wavelength of the transmitted signal.

This loss exhibits a straight line with a slope. This path loss slope is assumed two in free space and increases in dense urban environments. The path loss slope may decrease indoors due to the wave-guide effect of the walls [19]. This relation is called in the literature as attenuation due to distance [19], wide area median [20], long term median [20], path loss attenuation.

The second component is attributed to shadowing and multi-path caused by structures and terrain variations and is log-normally distributed with the mean value of the long-term median of the received signal and with a standard deviation of $4\text{ dB} \leq \sigma \leq 10\text{ dB}$ [19]. The value of σ depends on the environment. It has low values in rural areas, and high values in dense urban areas. This component is called in the literature as shadow fading, large-scale fading, slow fading, lognormal shadowing [19], and narrow area median [20].

The third component is caused by the traveling of a mobile through a standing wave pattern that is produced by the summing of the multi-path waves and is Rayleigh distributed around the narrow area median [20]. Rayleigh probability density function is given by [21].

$$f(r_k) = \frac{r_k}{p_k}\exp\left(-\frac{r_k^{\,2}}{2p_k}\right) \tag{2.4}$$

where,

p_k is the parameter of the density function, and $r_k \geq 0$.

This third component of radio wave propagation examines the fine details of the received signal and is called in the literature as Rayleigh fading, fast fading, small scale fading, short term fading, Rician fading (if the parameter, rice factor, of the rayleigh distribution is nonzero), and instantaneous variation [19]. The envelope process of this fast fading phenomenon is Rayleigh distributed if there is no strong direct component. Otherwise it is Rician.

Rayleigh fading is usually handled in mobile system designs by diversity techniques such as frequency hopping, multiple receivers, or correlators with variable delay lines and antenna diversity, and signal processing techniques such as bit interleaving, convolutional coding, and equalizers [13]. Shadow fading is handled by increasing transmitter power and co-channel reuse distance [13]. The fading due to distance, path loss exponent, is handled by handing off to the new base station when the signal from the old base station becomes unusable [13].

Finally, we should examine the effect of Fresnel zone. In multipath environments, diffraction of radio waves occurs when the wave front encounters an obstacle. Electromagnetic wave front is divided into zones of concentric circles, separated by $\lambda/2$. It can be assumed that the place where the radio wave hits the ground is Fresnel zone breakpoint. Within this point and the transmitter, radio wave propagates according to the free space path loss slope, since diffraction and multipath phenomena generally occur beyond this region. Fresnel zone breakpoint is related to the transmitter and receiver antenna heights and the frequency of the transmitted signal [22].

$$d_0 = d = 4h_1h_2 / \lambda \tag{2.5}$$

where,

h_1 is the transmitter antenna height,
h_2 is the receiver antenna height,
λ is the carrier wavelength,
d_0 is Fresnel zone breakpoint.

2.8. Mobile Location Estimation

Finding the location and the velocity of a mobile host is necessary to improve the performance of a wireless communication system by associating the mobile host with the correct cell, thus the base station.

Mobile positioning systems may be classified as belonging to three basic categories:

- Radiolocation methods
- Dead-reckoning methods
- Proximity Systems

Radiolocation methods estimate the mobile location using radio signals traveling between mobile host and some number of fixed-location base stations [23]. i.e. trilateration systems use radio signals from three fixed-location base stations. Dead reckoning methods estimate the mobile location by computing the distance and direction of travel from a known fixed point [23]. Proximity systems provide the location of vehicles by determining the relationship between the mobile and fixed locations, which are strategically placed throughout the area [23].

Several proposed mobile positioning techniques use signal strength measurement [24], angle detection [25,26], and arrival time measurement [27].

The mobile position estimation error in using signal strength measurements is due to the deviation of the measured *T*-second median. To reduce this error, it is necessary to keep the standard deviation of the estimated received signal median as small as possible by increasing the detection time *T*. However, to increase the efficiency of the mobile positioning system, it is necessary to reduce the time *T* [20].

In [20], zone selection rate (ZSR) is proposed to estimate the probability that a mobile is judged, using signal strength measurements, to exist in a certain zone.

External data, like from the Global Positioning System (GPS), can be used to estimate the location and the velocity of the mobile host and the mobile host can transmit its location and velocity with predetermined time intervals. However, this increases the mobile host complexity with the integration of a GPS system. So a system that uses the internal (existing) data to estimate the location and velocity is preferable. Received signal strengths from different base stations in the vicinity and their propagation times are known by the mobile hosts. In [24], a system is proposed to estimate locations and velocities of mobile hosts using signal strength measurements from fixed base stations whose locations are pre-known.

In Global System for Mobiles (GSM), each 0.48 *s*, the downlink (base to mobile) signal levels of six neighboring base stations are transmitted on a discrete scale from 0-63 [24]. However, obviously the received signal levels are subject to strong fluctuations caused by short-term fading, shadowing and reflections, which challenges the location estimation using received signal strength measurements. There are adaptive schema based on hidden markow models, neural networks and pattern recognition methods proposed to estimate the position of mobiles [24,28].

2.9. Mobile Velocity Estimation

The mobile velocity estimation can be employed in velocity adaptive handoff algorithms and hierarchical cellular networks. For velocity adaptive handoff algorithms, mobile velocity should be known to handle the handoff requests of fast moving mobiles immediately. For hierarchical cellular networks, mobile velocity needed to associate fast moving mobiles with the overlay macro-cells and low mobility users with the small coverage are micro-cells.

Three different velocity estimators are introduced and compared in [2] these estimators are based on:

- Level crossing rates (LCR)
- Zero crossing rates (ZCR)
- Covariance approximation methods

The level crossing rate (LCR) is defined as the average number of positive-going crossings per second that a signal makes of a predetermined level. Likewise, the zero crossing rate (ZCR) is defined as the average number of zero crossings that a signal makes per second [2].

The steps for using LCR of the envelope of the received signal for velocity estimation are:

- Determine the Root Mean Square (RMS) value of the received signal.
- Estimate the number of level crossings per second.
- Estimate the mobile velocity as a function of the carrier wavelength of the received signal and the number of level crossings per second.

Similarly, the steps for using ZCR of the in phase or quadrature components of the received signal for mobile velocity estimation are:

- Determine the mean of the in phase or quadrature components of the received signal.
- Estimate the number of zero crossings per second.
- Estimate the velocity as a function of the carrier wavelength of the received signal and the number of zero crossings per second.

Another technique to estimate the velocity of a mobile user, using cell dwell times was proposed in [29]. The cell dwell time of a mobile is a function of its velocity so given past cell dwell times of a mobile, one can estimate the velocity of a mobile using one of the two estimators.

Maximum Likelihood (ML) estimator estimates the velocity of a mobile as a function of n consecutive cell dwell times.

Minimum Mean Square Error (MMSE) estimator estimates the velocity of a mobile as a function of n consecutive cell dwell times assuming speed of a mobile is uniformly distributed between an interval a and b.

Employing selection diversity to estimate Doppler frequency and estimating velocity from the Doppler frequency is another technique to estimate the mobile velocity and proposed in [30]. Diversity reception was discussed in Section 2.6 of this document and recall that the same signal was received from different transmitters. Doppler frequency of the received signal is estimated using the switching rate of the receiver to the strongest signal.

2.10. Rerouting for Handoff

Handoff involves a sequence of events in the backbone network, including rerouting the connection and reregistering with the new base station [31]. One technique for rerouting is to establish an ad-on connection between the old and new base station. In this schema, the old base station acts as an anchor point and forwards the packets to the new base station so this technique is called packet forwarding. Another technique is to form the routes for all possible handoffs. So multiple connections to a single user are established. This technique is called virtual tree rerouting. Dynamic rerouting algorithms partially re-establish the user connection. Choosing appropriate rerouting algorithm depends on the traffic type. Real time traffic, i.e. voice, is not sensitive to loss but may be sensitive to delay to some degree where the data traffic, i.e. mail, is not sensitive to delay but may be sensitive to loss to some degree.

2.11. Interference in CDMA Systems

CDMA (Code Division Multiple Access) capacity is only interference limited while FDMA and TDMA are primarily bandwidth limited. Hence, a reduction in interference converts directly and linearly into an increase in capacity for CDMA systems. Multi-beamed or multi-sectored antennas reduce interference due to spatial isolation. Voice activity and spatial isolation make CDMA capacity larger. Path loss increases with the fourth power of distance in the free space or rural areas. CDMA can reuse the same (entire) spectrum for all cells. This increases the capacity by a large percentage of the normal reuse factor. Each user of a CDMA system occupies the entire allocated spectrum, employing a direct sequence spread spectrum waveform. Pilot signal is used in power control.

Signal to Noise ratio is given as follows [32]:

$$SNR = \frac{S}{(N-1)S} = \frac{1}{N-1} \tag{2.6}$$

where,

N: Number of users.

S: Desired signal power for the user, and interfering signal power for the interfering users.

SNR: Signal to Noise (interference) ratio.

Equation 2.6 is equivalent to:

$$E_b/N_0 = \frac{S/R}{(N-1)S/W} = \frac{W/R}{N-1} \tag{2.7}$$

where,

R: Information bit rate.

W: Carrier bandwidth.

S: Desired signal power.

$(N-1)S$: Noise (or interference).

E_b/N_0 is the energy required per bit to noise density ratio. An E_b/N_0 level is assumed which ensures operation at the level of bit error performance required for digital voice transmission.

With the inclusion of background noise E_b/N_0 becomes

$$E_b / N_0 = \frac{W/R}{(N-1)+(\eta/S)} \tag{2.8}$$

where,

η: Background noise.

So

$$N = 1 + \frac{W/R}{E_b/N_0} - \frac{\eta}{S} \tag{2.9}$$

where,

W/R: Processing gain.

E_b/N_0: Value required for adequate performance of modem and decoder.

Improved coding or modulation reduces E_b/N_0. When sectored antennas are used, capacity of CDMA system increases. Let us say N_s is the number of users per sector, then $N=3N_s$ for three sectors in each cell, each having 120^0 effective beam-widths. The interference sources seen by any antenna are approximately one-third of those seen by an omni-directional antenna. For voice communications, every talk spurt is followed by a silence gap. Let us say α is the voice activity factor. E_b/N_0 becomes:

$$\overline{E}_b/N_0 = \frac{W/R}{(N_S-1)\alpha + (\eta/S)} \tag{2.10}$$

Equation 2.10 is with sectored antennas and the voice activity monitoring. If we include the interference from remote co-channel cells, E_b/N_0 becomes

$$\overline{E}_b/N_0 = \frac{W/R}{(N_S-1)\alpha + (I/S) + (\eta/S)} \tag{2.11}$$

If we assume noise to signal ratio of the current access point is one, the soft capacity of the access point can be found from

$$N_S = \left(\left(\frac{W/R}{\overline{E}_b/N_0} - (I/S) - 1\right)\frac{1}{\alpha}\right) + 1 \tag{2.12}$$

In Equation 2.12, we need to find the remote co-channel cell interference to signal ratio *(I/S)* as follows; The generally accepted propagation model is an attenuation, which is the product of the fourth power of the distance and a lognormal random variable whose standard deviation is 8 dB [32]. That is the path loss between the subscriber and the cell site is proportional to $10^{(\xi/10)}\ r^{-4}$. r is the distance from subscriber to cell site and ξ is the Gaussian random variable with standard deviation σ=8 and zero mean. Fast fading (due largely to multi-path) is assumed not to affect the average power level. If the interfering subscriber is in another cell and at a distance r_m from its cell site and r_0 from the cell site of the desired user, the interfering user, when active, produces interference in the desired user's cell site, which is equal to

$$\frac{I(r_0,r_m)}{S}=\left(\frac{10^{(\xi_0/10)}}{r_0^4}\right)\left(\frac{r_m^4}{10^{(\xi_m/10)}}\right)=\left(\frac{r_m}{r_0}\right)^4 10^{(\xi_0-\xi_m)/10}\leq 1 \tag{2.13}$$

The first term in Equation 2.13 is due to the attenuation caused by distance and blockage to the given cell site, while the second term is the effect of power control to compensate for the corresponding attenuation to the cell site of the out-of-cell interferer [32]. We should sum the *I/S* values for all interfering co-channels.

2.12. Foundations of Fuzzy Logic Systems

Numbers or linguistic descriptions can represent information. For example, temperature can be represented by number 20^0F or by the linguistic description "cold." The description "cold" is fuzzy and may represent any temperature between 10^0F and 30^0F, which can be called the fuzzy set or fuzzy region for the fuzzy variable temperature [3]. Since humans usually think in terms of linguistic descriptions giving these descriptions some mathematical form helps exploit human knowledge. Fuzzy logic utilizes human knowledge by giving the fuzzy or linguistic description a definite structure [3].

We briefly review basic concepts of fuzzy sets and fuzzy logic, which will be useful in describing fuzzy logic systems [33].

Fuzzy Set: Let U be a collection of objects, and be called the universe of discourse. A fuzzy set F in U is characterized by a membership function μ_F: $U \rightarrow [0,1]$, with $\mu_F(u)$ representing the degree of membership of $u \in U$ in the fuzzy set F. Figure 2.3 shows the membership functions of three fuzzy sets, namely, "slow," "medium," and "fast" for the fuzzy variable speed of a car. In this example, the universe of discourse is all possible speeds of the car; that is, $U=[0,V_{max}]$, where V_{max} is the maximum speed of the car. At a speed of 45 mph, for example, the fuzzy set "slow" has the membership value 0.5, that is, $\mu_{slow}(45)=0.5$, the fuzzy set "medium" has membership value 0.5, that is, $\mu_{medium}(45)=0.5$, and the fuzzy set "fast" has membership value 0, that is, $\mu_{fast}(45)=0$

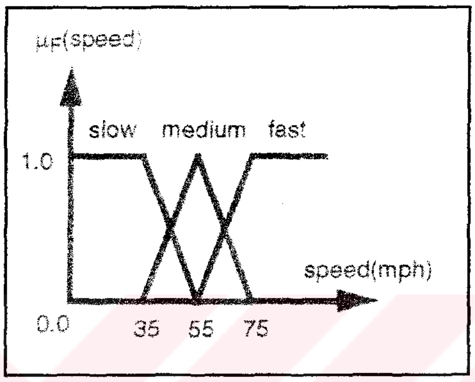


Figure 2.3. Membership functions of three fuzzy sets, namely, "slow", "medium," and "fast" for the speed of a car [33]

Support: The support of a fuzzy set F is the crisp set of all points $u \in U$ such that $\mu_F(u) > 0$.

Center: The center of a fuzzy set F is the point(s) $u \in U$ at which $\mu_F(u)$ achieves its maximum value.

Fuzzy Singleton: If the support of a fuzzy set F is a single point in U at which $\mu_F=1$, the F is called a fuzzy singleton.

Intersection and Union: Let A and B be two fuzzy sets in U. The intersection $A \cap B$ of A and B is a fuzzy set in U with membership function defined for all $u \in U$ by

$$\mu_{A \cap B}(u) = min\{\mu_A(u), \mu_B(u)\} \tag{2.14}$$

The union of $A \cup B$ of A and B is a fuzzy set in U with membership function defined for all $u \in U$ by

$$\mu_{A \cup B}(u)=max\{\mu_A(u), \mu_B(u)\} \tag{2.15}$$

A fuzzy logic system is directly related with fuzzy concepts (like fuzzy sets, linguistic variables, and so on) and fuzzy logic. The most popular fuzzy logic systems in the literature may be classified into three types [33]: pure fuzzy logic systems, Takagi and Sugeno's fuzzy system [34], and fuzzy logic systems with fuzzifier and defuzzifier. We will briefly describe the fuzzy logic systems with fuzzifier and defuzzifier. The basic configuration of fuzzy logic systems with fuzzifier and defuzzifier is shown in Figure 2.4.

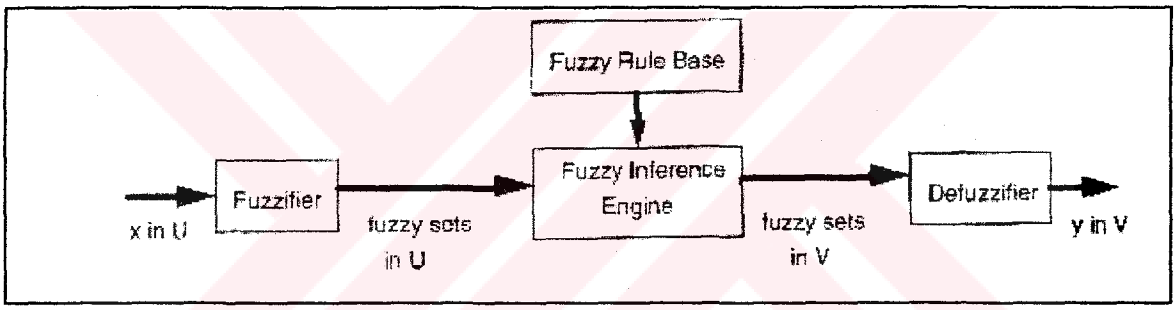


Figure 2.4. Basic configuration of fuzzy logic system with fuzzifier and defuzzifier [33]

Fuzzy Rule Base: A fuzzy rule base consists of a collection of fuzzy IF-THEN rules in the following form:

$$R^{(l)} : IF\ x_1\ is\ F_1^l\ and \ldots\ and\ x_n\ is\ F_n^l,\ THEN\ y\ is\ G^l \tag{2.16}$$

where,

F_i^l and G^l are fuzzy sets in $U_i \subset R$ and $V \subset R$, respectively,

$x_i \in U_i$ and $y \in V$ are linguistic variables.

Let M be the number of fuzzy IF-THEN rules in the form of (1.16) in the fuzzy rule base; that is, $l=1,2,\ldots,M$ in (1.16). The x_i and y are the input and output to the fuzzy logic system, respectively.

Fuzzy Inference Engine: In a fuzzy inference engine, fuzzy logic principles are used to combine the fuzzy IF-THEN rules in the fuzzy rule base into a mapping from fuzzy sets in $U=U_1 x \ldots\ldots x U_n$ to fuzzy sets in V. Each fuzzy If-THEN rule (1.16) determines a fuzzy set in V.

Fuzzifier: The fuzzifier performs a mapping from a crisp point $\underline{x} = (x_1, \ldots\ldots, x_n) \in U$ into a fuzzy set A^l in U.

Defuzzifier: The defuzzifier performs a mapping from fuzzy sets in V to a crisp point $y \in V$. One possible choice of this mapping is the *center average defuzzifier*, which is defined as

$$y = \frac{\sum_{l=1}^{M} \bar{y}^l (\mu_{B'}(\bar{y}^l))}{\sum_{l=1}^{M} (\mu_{B'}(\bar{y}^l))} \tag{2.17}$$

In Equation 2.17, $\bar{y}^l$ is the center of the fuzzy set G^l, that is, the point V at which $\mu_G{}^1(y)$ achieves its maximum value.

3. MOBILE INFRASTRUCTURE FOR RAPIDLY DEPLOYABLE COMMUNICATION NETWORKS

Mobile infrastructure of wireless communication networks satisfies rapid deployment and survivability requirements of some applications like military tactical communication and disaster area communication infrastructure deployment. A novel mobile infrastructure architecture and its resource allocation scheme called virtual cell layout (VCL) was proposed in [1,4].

3.1. Introduction to the VCL Architecture

Architectural elements of the proposed system in [1,4] are; Man Packed Radios (MPR), Radio Access Points (RAP), Unmanned Aerial Vehicles (UAV), and satellites. A schematic of the mobile subsystem is shown in Figure 3.1. In VCL, the communication area is tessellated into virtual cells as shown in Figure 3.2. Each virtual cell means a scramble code, a preamble code and a set of carriers.

MPR's are mobile terminals with the additional capability of acting as access point (AP) when needed. MPR's access to the Wide Area Subsystem by means of a RAP. When no RAP found in the vicinity, VCL helps MPR's to be clustered in between them and one MPR from the cluster elected as the head MPR. Other MPR's in the vicinity that do not have access to a RAP are registered to the head MPR using ad-hoc techniques. Details of these techniques can be found in [1,4]. The head MPR can access to the UAV or satellite tier to access to the Local Area or Wide Area Subsystem when no RAP to access is available. It is essential that a MPR can communicate in two carriers simultaneously [4].

RAP's can be thought as base stations. However, the difference is that they are mobile to satisfy the rapid deployment and survivability requirements. RAP's produce the mobile infrastructure of the mobile subsystem (MS). When a RAP is powered on, the first thing it requires is the geographical location of itself. There are various methods to provide the geographical location like Global Positioning System (GPS) or using the techniques discussed in Section 2.8. RAP maps that location information to the VCL and finds which

VCL cell it is in. Afterwards, the RAP searches the carriers to find one unused carrier, if it finds one; it goes into RUN state and starts to act as an access point to the wide area subsystem. If no unused carrier found, this evidences the existence of a RAP in RUN state in that virtual cell. New coming RAP replicates an un-replicated RAP. When the outage of the replicated RAP detected replicating RAP should take the resources of outage RAP. When RAP reaches the virtual cell border, it hands off to the resources of the new entered virtual cell if no carrier available found in the new cell, this again evidences the existence of a RAP in RUN state covering that virtual cell. So, new entering RAP forces its registered MPR's to handoff to the RAP in RUN state and tries to replicate a running RAP if it cannot replicate a RAP it goes into STANDBY state. RAPs are capable of communicating with *m* MPRs simultaneously and concentrate their traffic into a single trunk that can be established with UAVs, satellites, wide are subsystem (WAS) gateways or even with other RAPs [4].

UAV's and satellites provide an overlay architecture but when the power consumptions of MPR's, communication speeds, and security requirements are considered, it is preferred to communicate in the MPR or RAP tier level when possible.

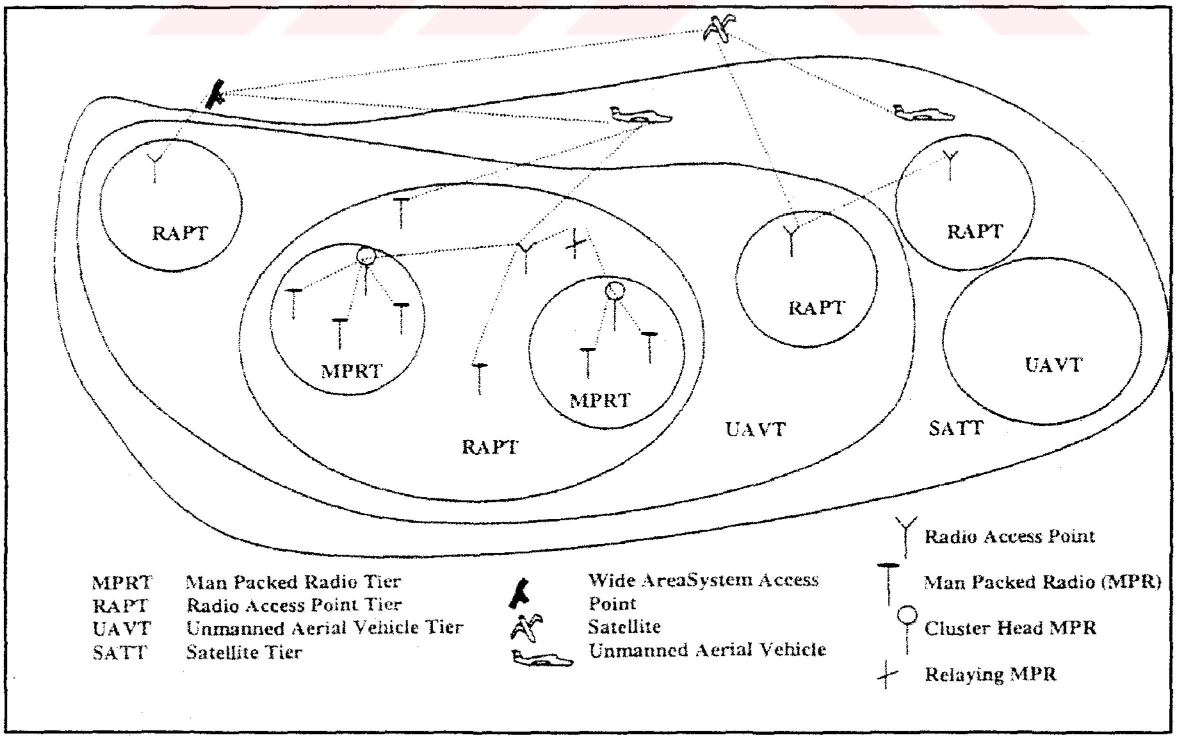


Figure 3.1. Multitier mobile subsystem [4]

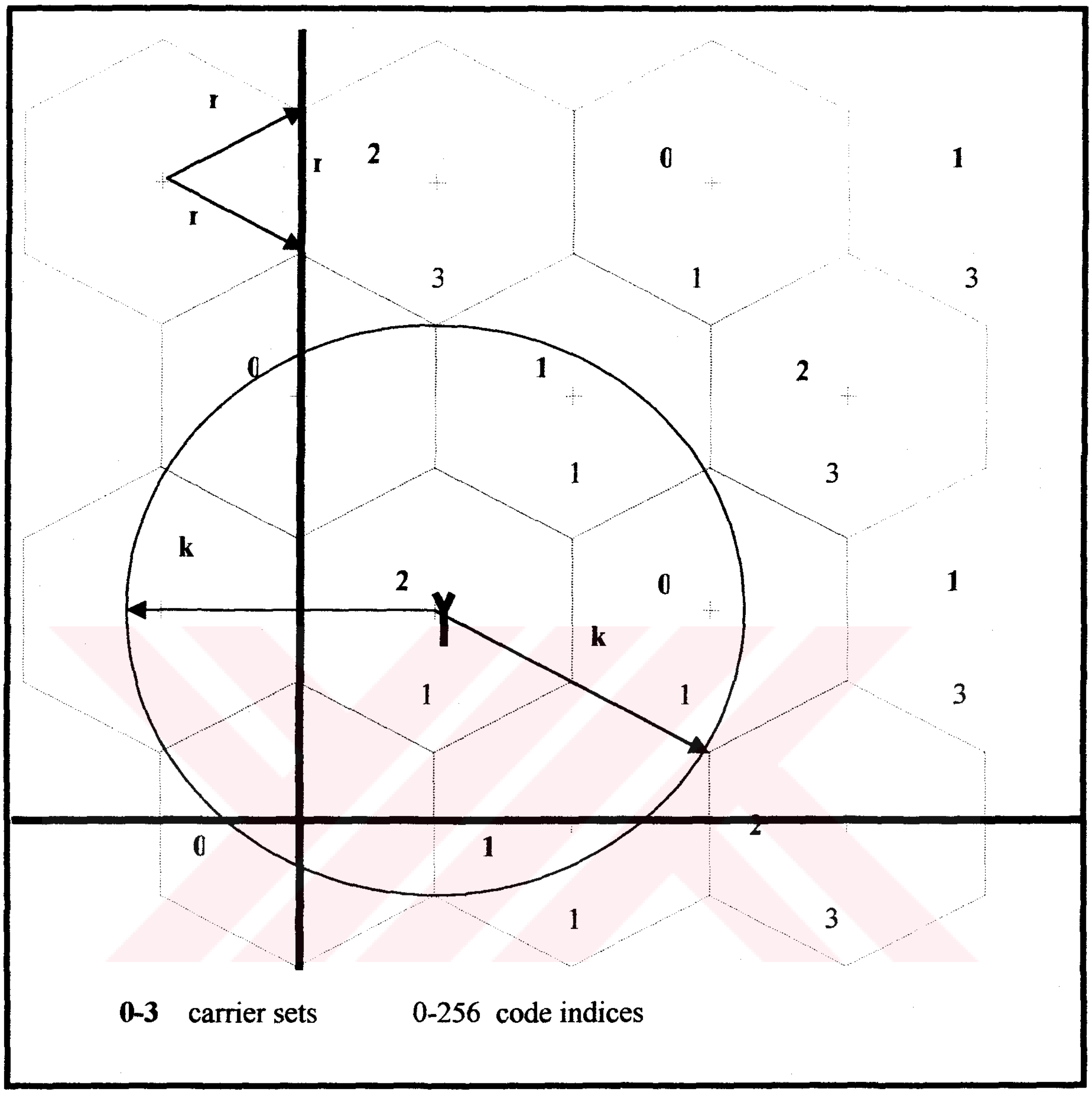


Figure 3.2. Virtual cell layout [4]

3.2. MPR Level Handoff Types for VCL

MPR's can be in one of the 11 states. These states are categorized as belonging to three main states, which are RELAY states, RUN states, and HEAD states. RELAY states are:

- RELAYRUN: An MPR is registered to a RAP and relaying another head MPR to the RAP that it is registered to.

- RELAYLINKED: An MPR is registered to another MPR that is in one of the HEADRUN or HEADRELAYED states and relaying another head MPR to the MPR that it is registered to.

RUN states are:

- RUN: An MPR is registered to a RAP.
- RUNLINKED: An MPR is registered to another MPR that is in one of the HEADRUN or HEADRELAYED states.
- RUNLINKEDPARTIAL: An MPR is registered to another MPR that is in HEADALONE state.

HEAD states are:

- HEADRUN: A HEAD MPR is registered to a RAP.
- HEADRELAYED: A head MPR is relayed to a RAP by means of an MPR that is in RELAYRUN state or relayed to an MPR that is in one of the HEADRELAYED or HEADRUN states by an MPR that is in RELAYLINKED state.
- HEADRELAYEDNOUSER: A HEADRELAYED MPR that has no registered MPRs
- HEADALONE: An MPR that is acting as a cluster head.
- HEADALONENOUSER:A HEADALONE MPR that has no registered MPRs.
- HEADALONENOUSERDUP: An MPR that was in RUNLINKEDPARTIAL state and waited enough in partially connected state to become a head and searching for a relay.

MPRs are changing their states to improve the connectivity of the network. A RELAYRUN MPR has most connectivity since it is registered to a RAP it has access to the Wide Area Subsystem (WAS) and it has the duty of relaying another cluster to the Wide Area Subsystem. So an MPR ultimately tries to be in RELAYRUN state. However, the dynamics of the environment may cause a MPR to be in a worse state. In Figure3.3, we can see a comprehensive cluster of a RAP that has access to the WAS. In Figure 3.4, we can see two possible comprehensive clusters that cannot access to the WAS but clustered separately.

First cluster in the Figure 3.4 has three MPRs. MPR in the HEADALONE state manages the cluster seen in the left side of the Figure 3.4. On the right side, we see an MPR in HEADALONENOUSER state. This MPR is alone. It could not find an access point to the WAS. Moreover it could not find a cluster head MPR that organizes a cluster. After waiting some time it declared itself as a cluster head. However no MPR has registered to it yet.

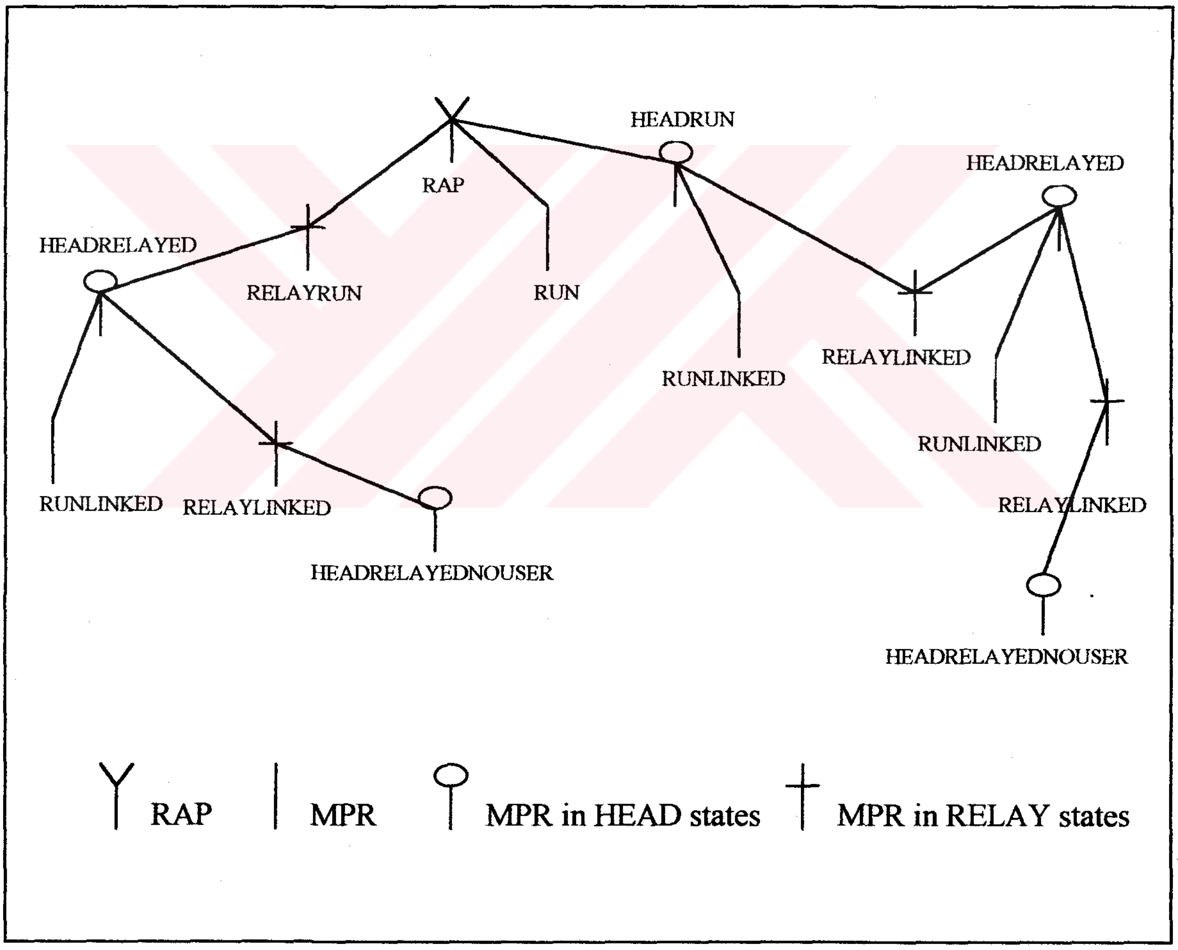


Figure 3.3. A comprehensive cluster that has WAS access

We have four types of handoffs for MPRs in the VCL architecture. We name them Type 1 through Type 4. Table 3.1 lists the MPR level handoff types for VCL.

RAPs in VCL architecture may have only inter-resource handoff caused by changing the virtual cell. Hence, we are mainly interested in MPR level handoffs. Table 3.2 shows possible state transitions related to MPRs and corresponding handoff types.

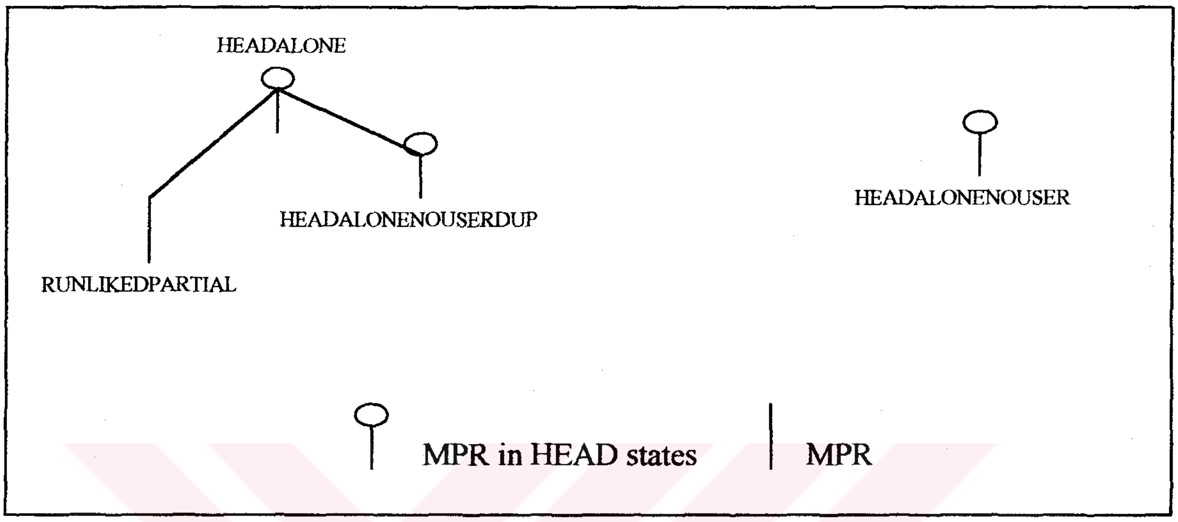


Figure 3.4. Two comprehensive self-clustered MPRs that cannot access to the WAS

Table 3.1. MPR level handoff types for VCL

Type 1: Inter-resource handoff of an MPR that is in HEADALONE or HEADALONENOUSER state because of changing its virtual cell.

Type 2: Handoff caused by decreasing signal strength or quality of service from the registered component.

Type 3: Handoff for improving the state to increase connectivity.

Type 4: Handoff caused by the registered component's handing off due to virtual cell change.

Table 3.2. Possible MPR state changes and their related handoff types

	RELAY-RUN	RUN	RELAY-LINKED	RUN-LINKED	HEAD-RUN	HEAD-RELAYED	HEADRELAYED NOUSER	HEAD-ALONE	HEADALONE-NOUSER	HEADALONE NOUSERDUP	RUNLINKED PARTIAL	STAND BY
RELAYRUN	2,4	0	2	---------	---------	--------------	----------------------	----------	----------------	-----------------	2	
RUN	0	2,4	----------	2	---------	--------------	----------------------	----------	----------------	-----------------	2	
RELAYLINKED	3	------	2,4	0	---------	--------------	----------------------	----------	----------------	-----------------	2	
RUNLINKED	---------	3	0	2,4	---------	--------------	----------------------	----------	----------------	-----------------	2	
HEADRUN	---------	0	----------	---------	2,4	--------------	----------------------	0	----------------	-----------------	-----------------	
HEADRELAYED	---------	------	----------	----------	3	4	0	0	----------------	-----------------	-----------------	
HEADRELAYED NOUSER	---------	3	----------	3	---------	--------------	4	----------	2	-----------------	-----------------	
HEADALONE	---------	------	----------	----------	0	0	----------------------	----------	0	-----------------	-----------------	
HEADALONENOUSER	---------	3	----------	3	---------	--------------	0	----------	----------------	-----------------	3	
HEADALONENOUSER DUP	---------	3	----------	0, 3	---------	--------------	0	----------	----------------	4	0,2	
RUNLINKEDPARTIAL	---------	3	----------	0,3	---------	--------------	----------------------	----------	----------------	0	2,4	
STANDBY												

0: State Change that does not cause handoff.

1: Type 1 handoff: changing virtual cell for Head MPR.

2: Type 2 handoff: decreasing signal strength from the registered component.

3: Type 3 handoff: improving the state to increase connectivity.

4: Type 4 handoff: because, registered component handing off due to virtual cell change.

3.3. Algorithms Related to Handoff for MPRs in VCL

The flow diagram related to the handoff decision for MPRs in RUN or RELAYRUN states is shown in Figure 3.5. MPR in RUN or RELAYRUN state searches for a RAP, which is better than the currently registered RAP. Meaning of 'better' changes according to the handoff decision algorithm used. For Received Signal Strength (RSS) based algorithm, better access point[1] is the one from which the received pilot signal strength is stronger than the currently registered access point's pilot signal. For RSS with threshold handoff decision algorithm 'better' means the same but MPR does not search for a better access point unless the pilot signal from the currently registered access point does not drop below a predetermined threshold level. Moreover, for RSS with hysteresis handoff decision algorithm meaning of better does not change but MPR does not think handing off to the candidate access point unless its received pilot signal does not get better an amount equal to a predetermined hysteresis level than the currently registered access point's received pilot signal strength. For multi-criteria handoff decision algorithm 'better' access point is the one having larger membership value than the currently registered access point. The Details of multi-criteria handoff decision algorithm and the methodology to calculate the membership value are described in Chapter 4.

If there is a better RAP in the vicinity, we perform a Type 2 handoff to the newfound RAP. If we cannot find a better RAP in the vicinity, we check the pilot signal from the currently registered RAP. If it is strong enough, we do nothing but if the pilot signal dropped below the minimum acceptable signal level, we search for a relayed head MPR. If we can find one in the vicinity, we perform a Type 2 handoff to the 'best' relayed head MPR. 'Best' means 'better' than all. If we cannot find one, we search for a not relayed head MPR. If we can find one in the vicinity, we again perform a Type 2 handoff to the 'best' not relayed head MPR. If we cannot find, we break the ongoing and relayed calls and go into STANDBY state.

---

[1] For MPRs in RUN, RELAYRUN or HEADRUN state a better access point is a RAP.
For MPRs in RUNLINKED or RELAYLINKED state a better access point is a relayed head MPR.
For MPRs in RUNLINKEDPARTIAL or HEADALONENOUSERDUP state a better access point is a not relayed head MPR.

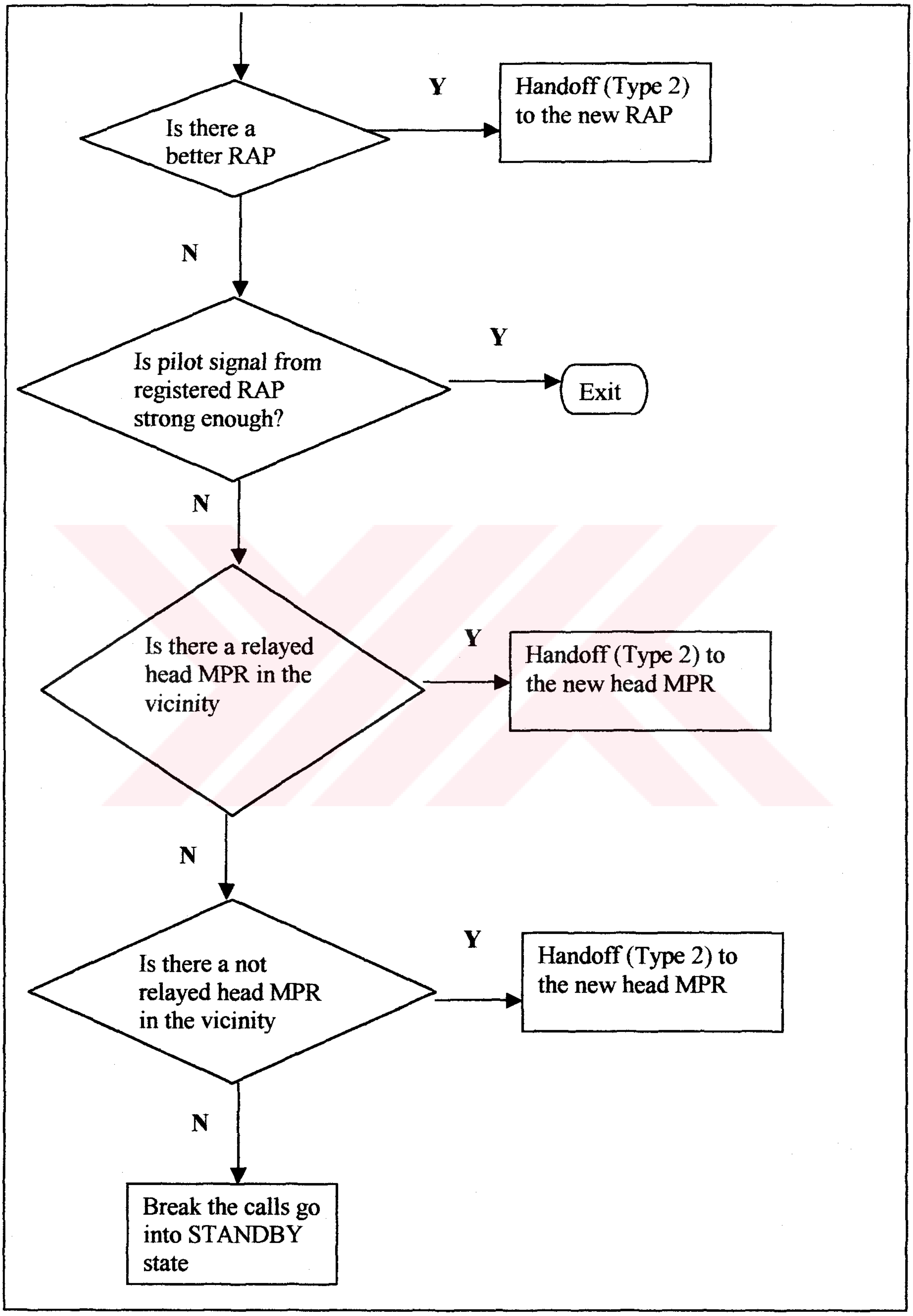


Figure 3.5. Flow diagram related to handoff decision for MPRs in RUN or RELAYRUN state

The flow diagram related to the handoff decision for MPRs in RUNLINKED or RELAYLINKED states is shown in Figure 3.6. MPR in RUNLINKED or RELAYLINKED state searches for a RAP, if it can find one in the vicinity, it performs a Type 3 handoff to the found RAP. If it cannot find one, it searches for a 'better' relayed head MPR. If it can find one in the vicinity it performs a Type 2 handoff to the new found head MPR. If it cannot find one and the pilot signal received from the registered head MPR is below the minimum level, it searches for a not relayed head MPR in the vicinity. If it can find one, it performs a Type 2 handoff to the new found head MPR. If it cannot find one, it breaks the calls generated and relayed and goes into STANDBY state.

The flow diagram related to the handoff decision for MPRs in RUNLINKEDPARTIAL or HEADALONENOUSERDUP states is shown in Figure 3.7. MPR in RUNLINKEDPARTIAL or HEADALONENOUSERDUP state searches for a RAP if there is no active call going on or the pilot signal from the registered HEAD MPR is below the minimum signal level. Since clusters formed by not relayed head MPRs cannot access to the outside of their own cluster, handing off from such a cluster to another access point may cause an ongoing call to terminate because the destination of the active call will probably cannot be reachable from new access point so MPRs in RUNLINKEDPARTIAL or HEADALONENOUSERDUP states will wait their active calls to finish before handing off when the pilot signal from the currently registered not relayed head MPR is strong enough. If MPR can find a RAP in the vicinity, it performs a Type 3 handoff to that RAP. If there is no RAP in the vicinity it searches for a relayed head MPR in the vicinity, if it can find one, it performs a Type 3 handoff to that head MPR. If there is no relayed head MPR in the vicinity, it searches for a 'better' not relayed head MPR. If it can find one, it performs a Type 2 handoff to that head MPR. If it cannot find any not relayed head MPR and the pilot signal from the registered head MPR is below the minimum level it breaks the generated calls and goes into STANDBY state.

The flow diagram related to the handoff decision for MPRs in HEADRUN state is shown in Figure 3.8. MPR in HEADRUN state searches for a better RAP. If it can find one, it performs a Type 2 handoff to that RAP. If it cannot find one and if the received pilot signal from the registered RAP is below the minimum acceptable level, it breaks the

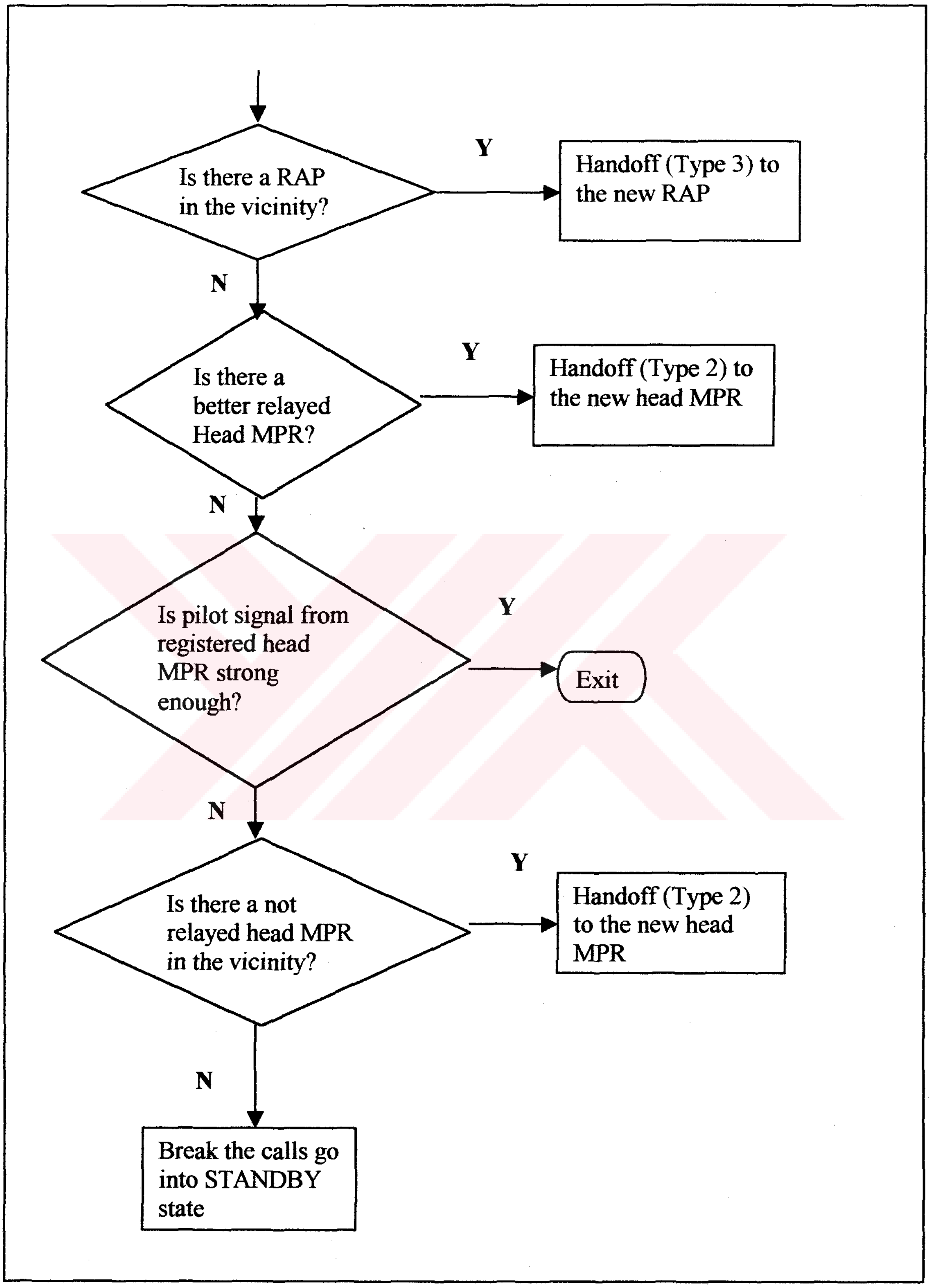


Figure 3.6. Flow diagram related to handoff decision for MPRs in RUNLINKED or RELAYLINKED state

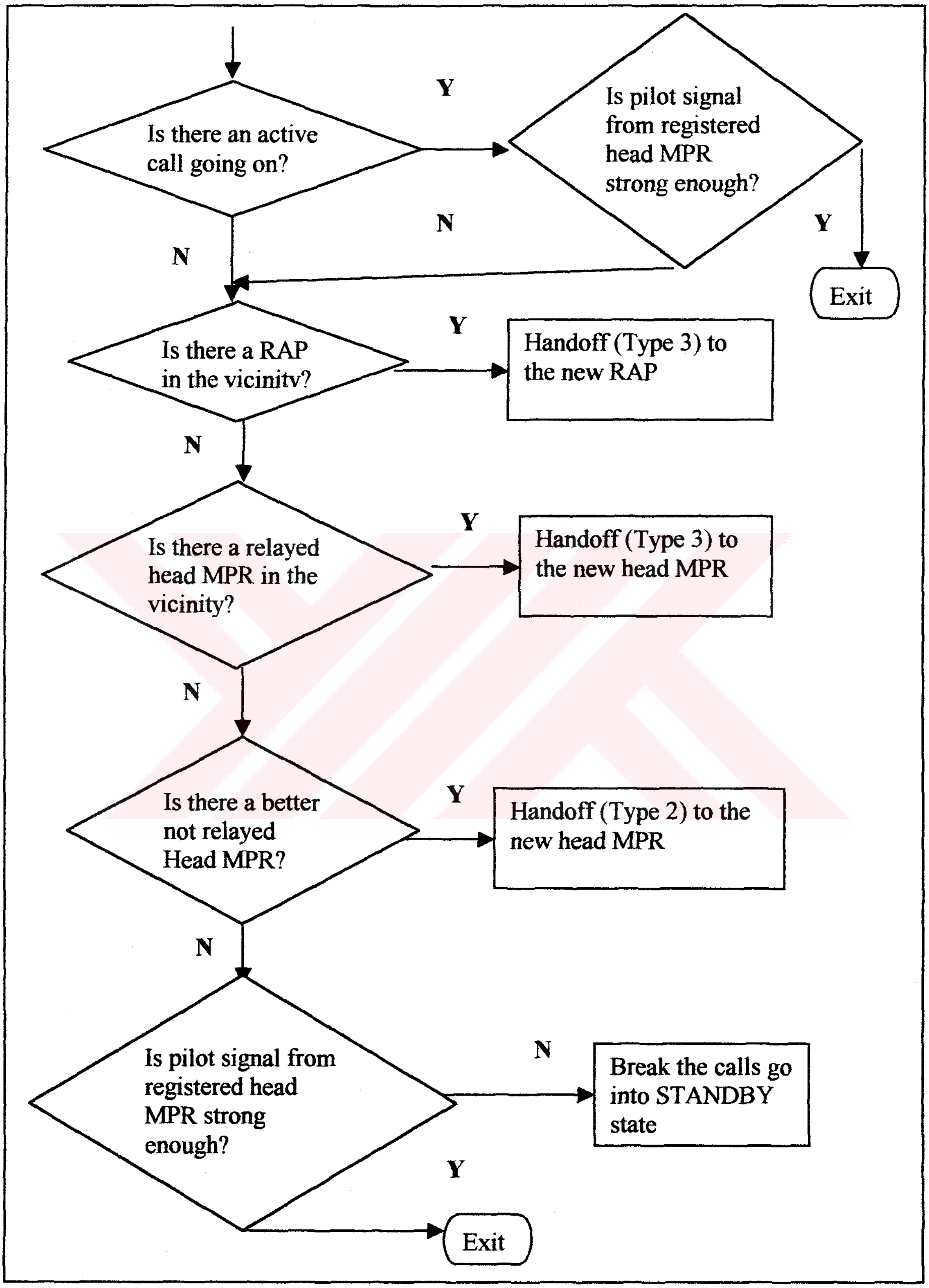


Figure 3.7. Flow diagram related to handoff decision for MPRs in RUNLINKEDPARTIAL or HEADALONENOUSERDUP state

uplink calls and deregisters from upper layers itself and the MPRs registered to it and goes into HEADALONE state as being the head of its not relayed cluster.

The flow diagram related to the handoff decision for MPRs in HEADRELAYED state is shown in Figure 3.9. MPR in HEADRELAYED state searches for a RAP in the vicinity if it can find one, it performs a Type 3 handoff to that RAP.

The Flow diagram related to the handoff decision for MPRs in HEADRELAYEDNOUSER state is shown in Figure 3.10. MPR in HEADRELAYEDNOUSER state searches for a RAP in the vicinity if it can find one, it performs a Type 3 handoff to that RAP. If it cannot find a RAP, it searches for a relayed head MPR in the vicinity if it can find one it performs a Type 3 handoff to the found head MPR.

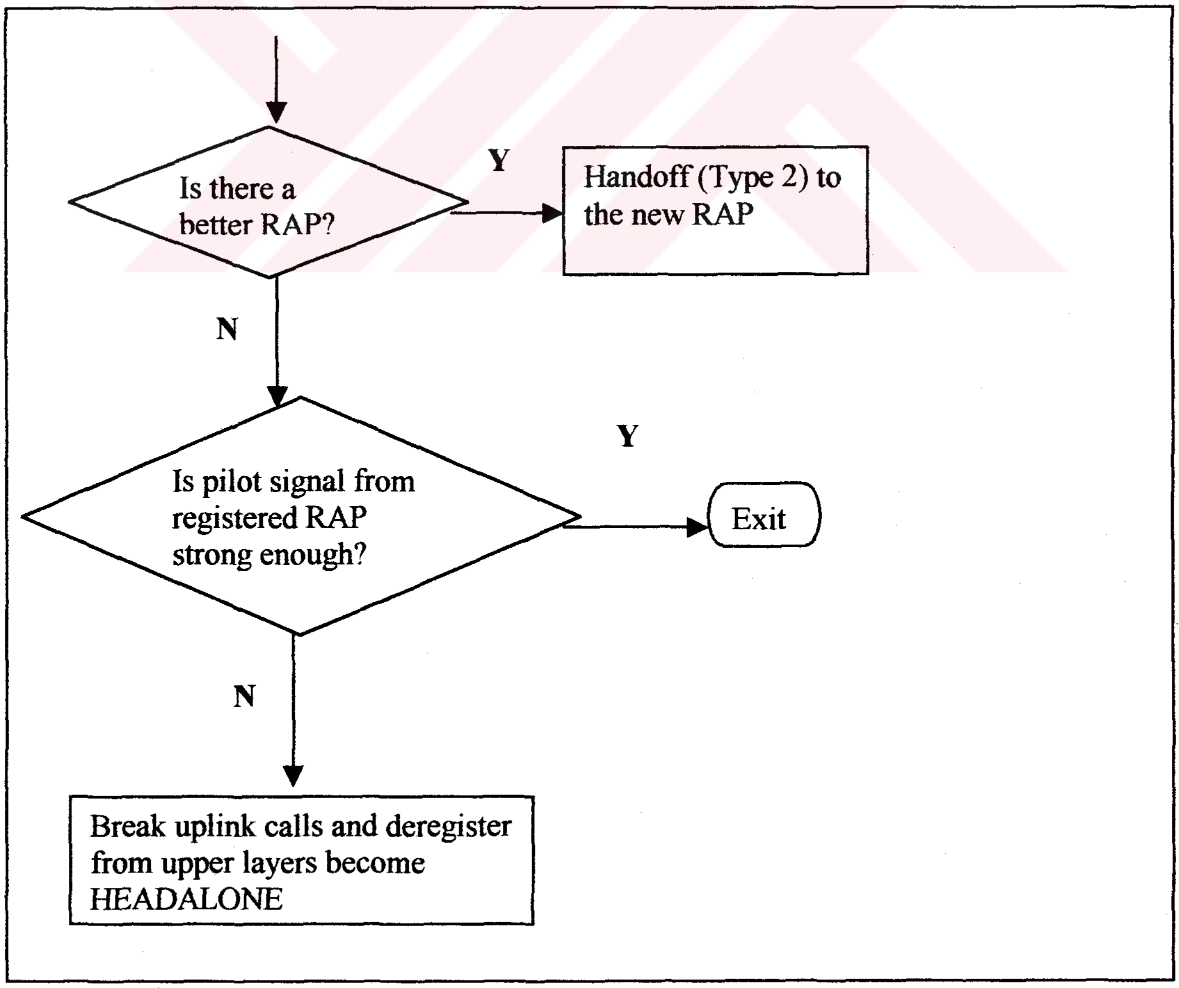


Figure 3.8. Flow diagram related to handoff decision for MPRs in HEADRUN state

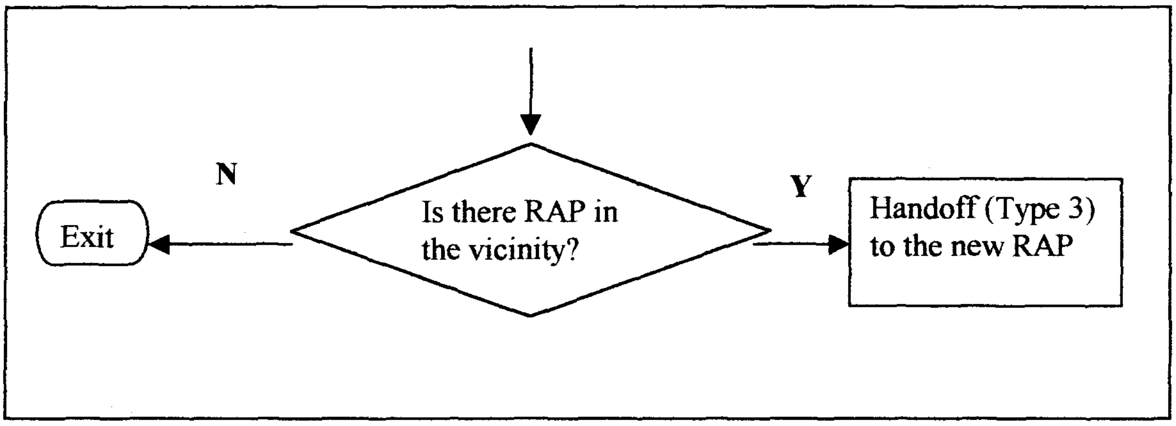


Figure 3.9. Flow diagram related to handoff decision for MPRs in HEADRELAYED state

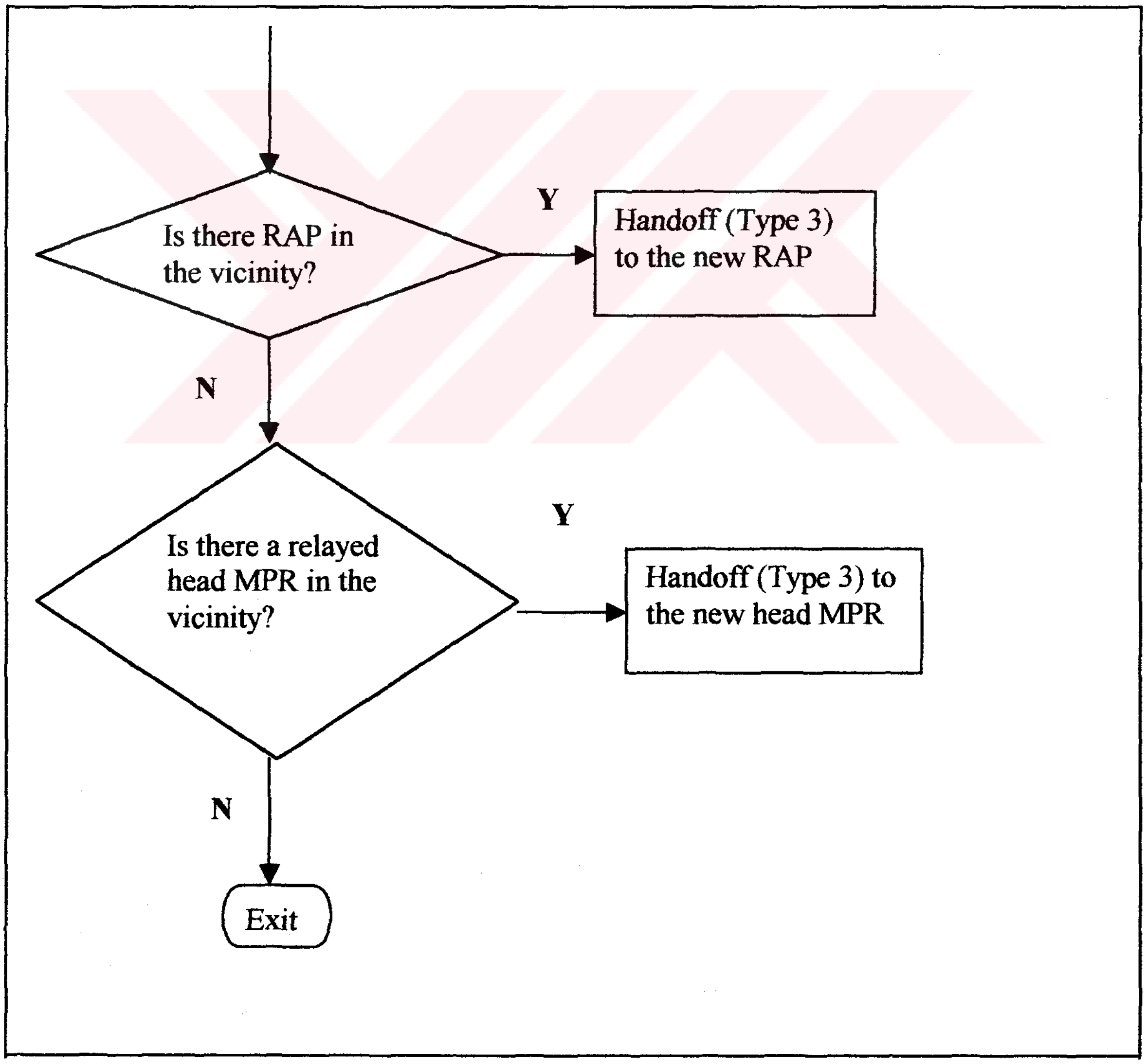


Figure 3.10. Flow diagram related to handoff decision for MPRs in HEADRELAYEDNOUSER state

4. HANDOFF DECISION ALGORITHM FOR MOBILE INFRASTRUCTURE OF RAPIDLY DEPLOYABLE COMMUNICATION NETWORKS

We propose a handoff decision stage algorithm based on fuzzy inference systems for the systems having a mobile infrastructure. With slight modifications, the algorithm can be used for systems having an immobile infrastructure.

Our prior knowledge about the systems with mobile infrastructure is that, mobiles move in clusters to achieve a goal, since we use the mobile infrastructure for military or disaster based applications. So the likelihood of a cluster to have an access point moving together with the cluster is very high. Hence, in our algorithm, we integrated the speed and the direction components to the handoff decision parameters to find the access point of our cluster if it exists.

Third generation systems use CDMA as their air interface. CDMA systems are mainly interference limited. Increasing the interference reduces directly the system capacity so we should consider the interference in our algorithm.

4.1. Multi-criteria Handoff Decision Algorithm

We employed the fuzzy logic system with center average defuzzifier, product-inference rule and, singleton fuzzifier. Details of the fuzzy logic systems are discussed in Section 2.12. Figure 4.6 shows the block diagram of the proposed system.

We defined four-dimensional pattern vector for current access point:

$$PV_C = [RSS_C; SCU_C; \Delta\theta_C; \Delta V_C] \tag{4.1}$$

And four-dimensional pattern vector for candidate access point:

$$PV_N=[RSS_N;\ SCU_N;\ \Delta\theta_N;\ \Delta V_N] \tag{4.2}$$

where;

RSS_C: Received Signal Strength from currently serving access point

RSS_N: Received Signal Strength from candidate access point

SCU_C: Used soft capacity of the currently serving access point

SCU_N: Used soft capacity of the candidate access point

$\Delta\theta_C$: Direction difference between MPR and currently serving Access Point (APC)

$$\begin{gathered}\Delta\theta_C=|\,Direction_{MPR}-Direction_{APC}|\\ If\ (\Delta\theta_C>180)\ then\ (\Delta\theta_C=360-\Delta\theta_C)\end{gathered} \tag{4.3}$$

$\Delta\theta_N$: Direction difference between MPR and candidate Access Point (APN)

$$\begin{gathered}\Delta\theta_N=|\,Direction_{MPR}-Direction_{APN}|\\ If\ (\Delta\theta_N>180)\ then\ (\Delta\theta_N=360-\Delta\theta_N)\end{gathered} \tag{4.4}$$

ΔV_C: Velocity difference between MPR and currently serving Access Point

$$\Delta V_C=|Speed_{APC}-Speed_{MPR}| \tag{4.5}$$

ΔV_N: Velocity difference between MPR and candidate Access Point

$$\Delta V_N=|Speed_{APN}-Speed_{MPR}| \tag{4.6}$$

The mobile monitors the pilot signal of the currently serving access point and candidate access points. These measurements are the current (RSS_C) and candidate (RSS_N) received signal strengths. Used soft capacity of an access point is the number of used channels of that access point. Soft capacity of an access point can be found from Equation 2.12 as described in Section 2.11. $\Delta\theta$ is the direction difference and if the mobile and the access point are going in the same direction it is zero and if they are going in opposite directions, it is 180. So $\Delta\theta$ is a value between zero and 180. $\Delta\theta_C$ and $\Delta\theta_N$ can be calculated from Equation 4.3 and Equation 4.4 respectively. ΔV is the velocity difference between the mobile and the access point if they are going with the same speed; it is zero. ΔV_C and ΔV_N can be calculated from Equation 4.5 and Equation 4.6 respectively.

These four measurements are input to a fuzzifier working on the mobile. Duty of the fuzzifier is to map elements of the input pattern vector to fuzzy variables [33] having three fuzzy sets, namely LOW (L), MEDIUM (M), and HIGH (H). So each element of the input pattern vector, P_i, is mapped to a fuzzy variable, PF_i. The first element of the input pattern vector is RSS_C. This value is called P_1, which is mapped to a fuzzy variable PF_1 by the fuzzifier. PF_i is the three-tuple representing the membership values of P_i to the fuzzy sets HIGH, MEDIUM, and LOW.

According to the maximum transmission power of the access point and the environment propagation parameters, the range of the access point is d meters. The mean received signal strength at distance $2d/3$ from an access point is k dB and the mean received signal strength at distance $d/3$ from access point is t dB. Figure 4.1 shows the membership functions of P_1.

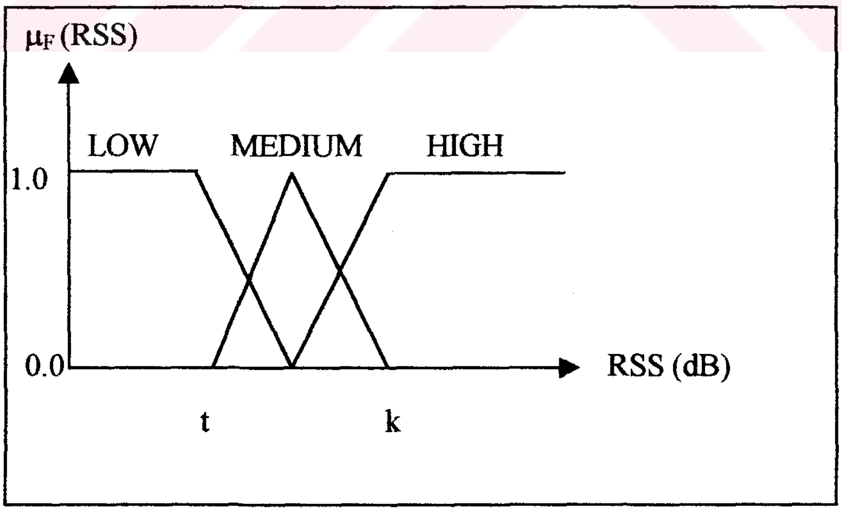


Figure 4.1. Membership functions of three fuzzy sets, namely, 'LOW', 'MEDIUM', and 'HIGH' for the RSS

Soft capacity of an access point can be found as explained in Section 2.11. Increasing interference reduces the soft capacity of an access point. Let us assume the access point has *c* channels soft capacity. If number of channels used in the access point is *SCU*, Membership functions for P_2 are as in the Figure 4.2:

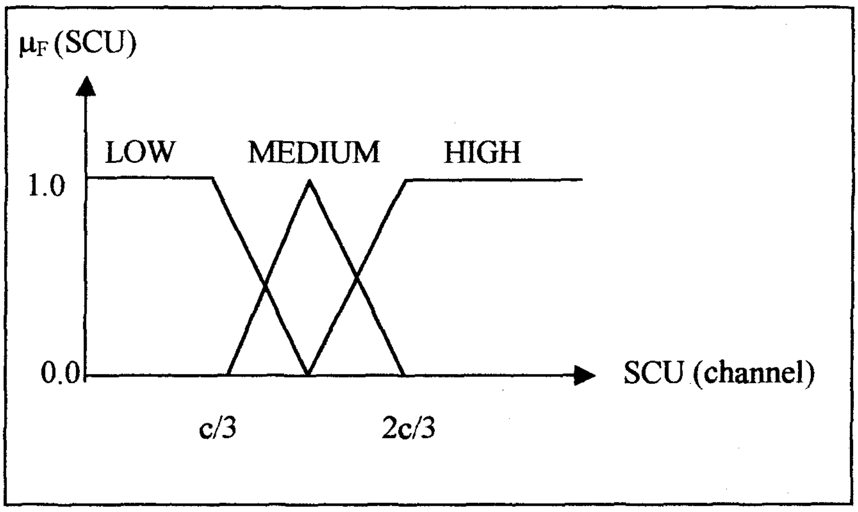


Figure 4.2. Membership functions of three fuzzy sets, namely, 'LOW', 'MEDIUM', and 'HIGH' for the SCU

The direction of movement difference between the access point and the mobile is $\Delta\theta$, which is the third element, P_3, of the input pattern vector. Membership functions for P_3 are as in the Figure 4.3:

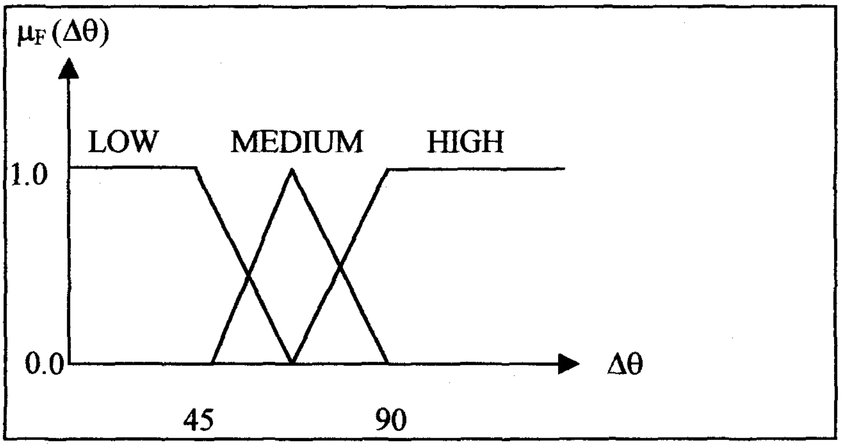


Figure 4.3. Membership functions of three fuzzy sets, namely, 'LOW', 'MEDIUM', and 'HIGH' for the $\Delta\theta$

The velocity difference between the access point and the mobile is ΔV, which constitutes the fourth element, P_4, of the input pattern vector. Membership functions for P_3 are as in the Figure 4.4:

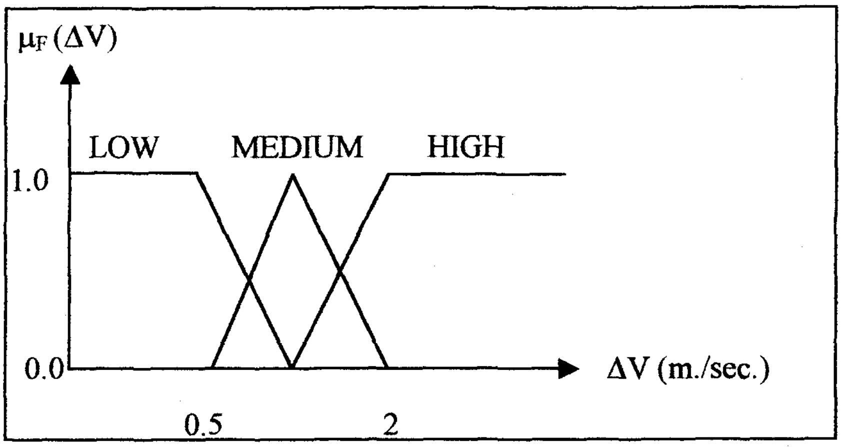


Figure 4.4. Membership functions of three fuzzy sets, namely, 'LOW', 'MEDIUM', and 'HIGH' for the ΔV

Now, we have the four-dimensional fuzzy pattern vector as input to the fuzzy inference engine.

$$PV_F=[PF_1,PF_2,PF_3,PF_4] \tag{4.7}$$

PF_i is the three-tuple representing the membership values of P_i to the fuzzy sets HIGH, MEDIUM, and LOW. If P_4 has the value of 0.75 *m/sec.* Corresponding PF_4 is [0.5,0.5,0]. Since, $\mu_{LOW}(0.75)=0.5$, $\mu_{MEDIUM}(0.75)=0.5$, $\mu_{HIGH}(0.75)=0$ as apparent from the Figure 4.4.

We should obtain rules for our fuzzy rule base. Rules are classified to one of the nine classes. So the class of each rule is a value between one and nine and gives the degree of membership for a mobile to the access point. The value of one is the lowest degree of the membership and a possible handoff to another access point will occur. And the value of nine is the highest degree of the membership and the mobile will not handoff to another access point. Since there are four fuzzy variables and three fuzzy sets there are total of $3^4=81$ rules. Figure 4.5 shows example rules in the fuzzy rule base.

Rule 1:

If P_1 is L and P_2 is H and P_3 is H and P_4 is H then output is 1

Rule 2:

If P_1 is L and P_2 is M and P_3 is H and P_4 is H then output is 2

•

•

•

Rule 81:

If P_1 is H and P_2 is L and P_3 is L and P_4 is L then output is 9

Figure 4.5. Rules in the fuzzy rule base

In Rule 1, we have low received signal strength from the access point, high amount of the access point's soft capacity is used, access point and mobile are going nearly opposite directions, and there is high speed difference between the access point and the mobile. So, each element of the input pattern vector votes *badly* for this access point. So agreement for the badness of the access point is four. Similarly, In Rule 81, we have high received signal strength from the access point, low amount of the access point's soft capacity is used, access point and mobile are going nearly the same directions, and there is low speed difference between the access point and the mobile. So, each element of the input pattern vector votes *well* for this access point. So agreement for the goodness of the access point is four. Table 4.1 shows the classes of the rules corresponding to the agreement about the access point.

Table 4.1. Classes of the rules corresponding to the result of voting between the elements of the input pattern vector

Agreement	rule class	Agreement	rule class
4 BAD	1	1 GOOD	6
3 BAD	2	2 GOOD	7
2 BAD	3	3 GOOD	8
1 BAD	4	4 GOOD	9
DRAW	5		

We used the product-inference rule in our fuzzy inference engine due to its simplicity in implementation. Hence, contribution of each rule in the fuzzy rule base is given by Equation 4.8 [33].

$$\textit{Contribution of each rule} = \prod_{i=1}^{4} \mu_{F_i}(P_i) \tag{4.8}$$

where,

$\mu_{F_i}(P_i)$ is the membership value of the P_i to fuzzy set F_i. And obtained from Figures 4.1 - 4.4 for P_1 through P_4.

We have 81 rules and we use center average defuzzifier so the output of the defuzzifier is given by Equation 4.9 [33].

$$\textit{Membership value of the access point} = \frac{\sum_{l=1}^{81} y^l (\prod_{i=1}^{4} \mu_{F_i}(P_i))}{\sum_{l=1}^{81} (\prod_{i=1}^{4} \mu_{F_i}(P_i))} \tag{4.9}$$

where,

y^l is the output of the rule l.

Each mobile keeps a set of access points whose pilot signals are received. Let us call this set as SoA. The calculations above are done for each element of SoA. The membership values of the mobile to the candidate access points are calculated. The membership value of the mobile to the current access point and the membership value of the mobile to the candidate access points are input to the comparator whose output is the handoff decision and target. If the membership value to the current access point is dropped below the membership value threshold and the access point having a membership value better than the current access point's membership value an amount of at least the membership hysteresis value is candidate access point to handoff. That is;

Handoff to the access point i (AP_i) if ($M_C < M_{threshold}$) AND ($M_{Ni} - M_{hysteresis} > M_C$) (4.10) where;

M_C: Membership value of current access point

$M_{threshold}$: Membership value threshold.

$M_{hysteresis}$: Membership value hysteresis.

M_{Ni}: Membership value of access point i (AP_i).

$i \in [1$, number of access points that the mobile is in range of].

$AP_i \in SoA$ and mobile has the largest membership value for AP_i among its set of candidate access points SoA.

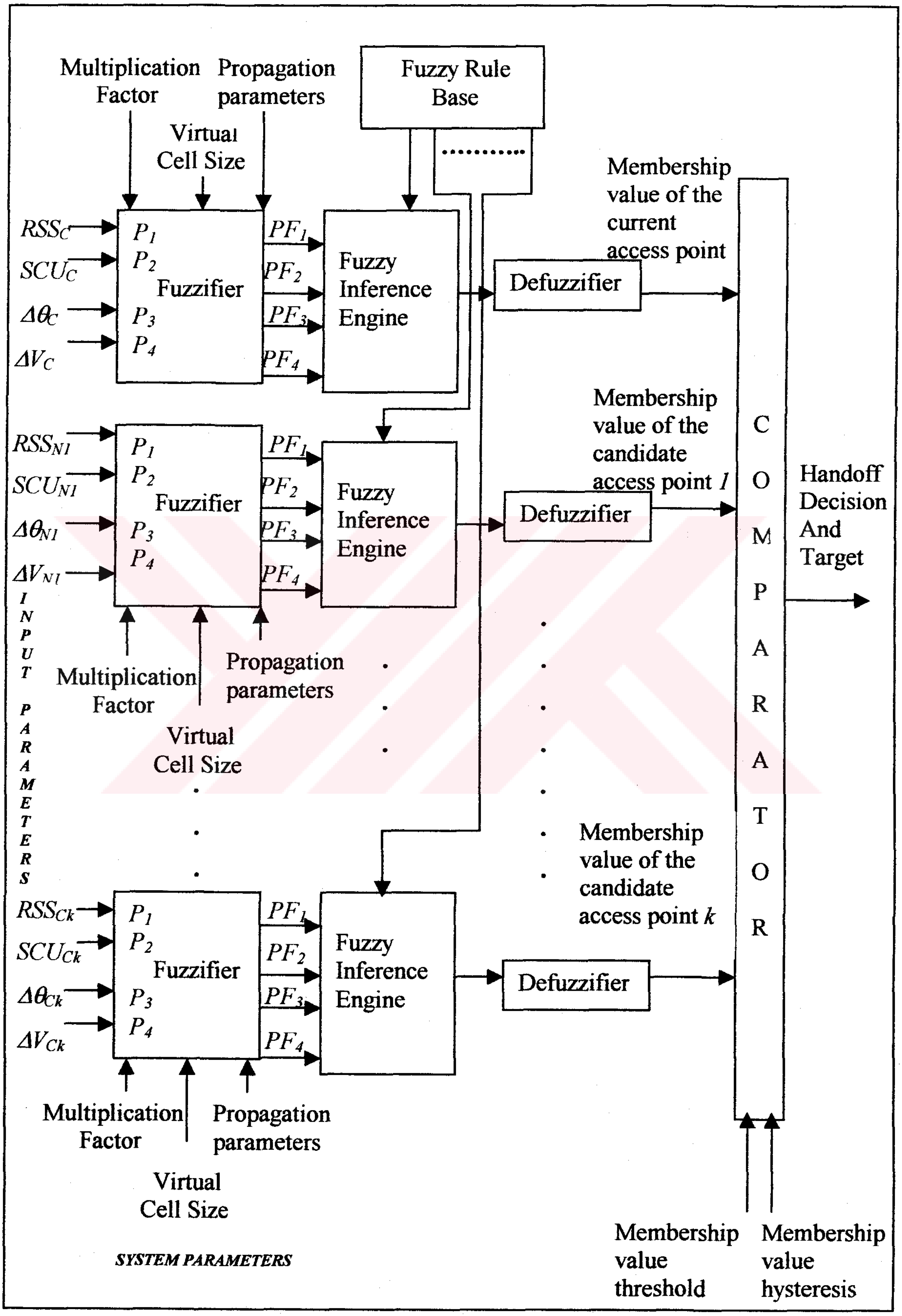


Figure 4.6. Block diagram of the handoff decision system

5. PERFORMANCE EVALUATION OF HANDOFF ALGORITHMS FOR MOBILE INFRASTRUCTURE OF MOBILE COMMUNICATION NETWORKS

We use simulation to evaluate the performance of the handoff algorithms for the mobile infrastructure of the rapidly deployable VCL networks.

Our mobility model is based on a real war game simulation data obtained from JTLS [35,36]. We used two scenarios, first has two hours duration and 34 units, 4466 MPRs and 26 RAPs, second has thirty minutes duration and 28 units, 3452 MPRs and 20 RAPs Simulation area is 85 km x 40 km in size.

Our call arrival pattern is Poisson, in which call interarrival times are exponentially distributed. Call durations are also exponentially distributed. The exponential distribution for the call inter arrival times is a good approximation in the battlefield, because war fighters try to communicate with short time intervals in certain period of times, and if the time intervals between the calls get larger than the mean intervals, they get much larger than the mean. This is the same in call duration times [4]. Mean values of the distributions are determined according to a statistical study done in [1,4,37]. In this statistical study, mean values change according to the unit type and posture.

Since we are in an open rural area, we used the propagation model with two dB path loss exponent and free space propagation up to the Fresnel breakpoint, shadowed propagation with four dB path loss exponent and four dB shadow fading standard deviation after the Fresnel breakpoint. We used two m transmitter and receiver antennas and 1800 MHz carrier frequency, which make Fresnel breakpoint about 100 m away from the access point.

We also assumed one carrier with five Mhz bandwidth in VCL cell. And five minutes before a connecting data call transmission is blocked. If a connecting real time traffic like voice, teleconference, video teleconference cannot reach to destination due to lack of network resources, unreachable destination or busy destination, it is blocked immediately. After a certain time, a reattempt for that call may occur. We assumed the maximum E_b/N_0 value as five for adequate communication quality.

We used two metrics for the comparison of handoff algorithms for the mobile infrastructure. These are the ratio of blocked calls due to lack of network resources to total calls and the number of MPR handoffs. A sophisticated algorithm should have low values for both.

We examined handoff algorithms for VCL cell radius 1000 m, 2000 m, and 4000 m. The multiplication factor determines the real coverage area of an access point. For example, for the multiplication factor two with 2000 m VCL cell radius, the real coverage area of an access point will be 4000 m (2x2000). For each VCL cell radius, we examined the multiplication factor one and two.

Each performance value reported in this section is the mean of 15 runs obtained by changing the random seeds that affect the initial deployment of the units, call generation probabilities, call durations, and the destinations of the calls. Error bars on each data point are representing 95 per cent confidence intervals.

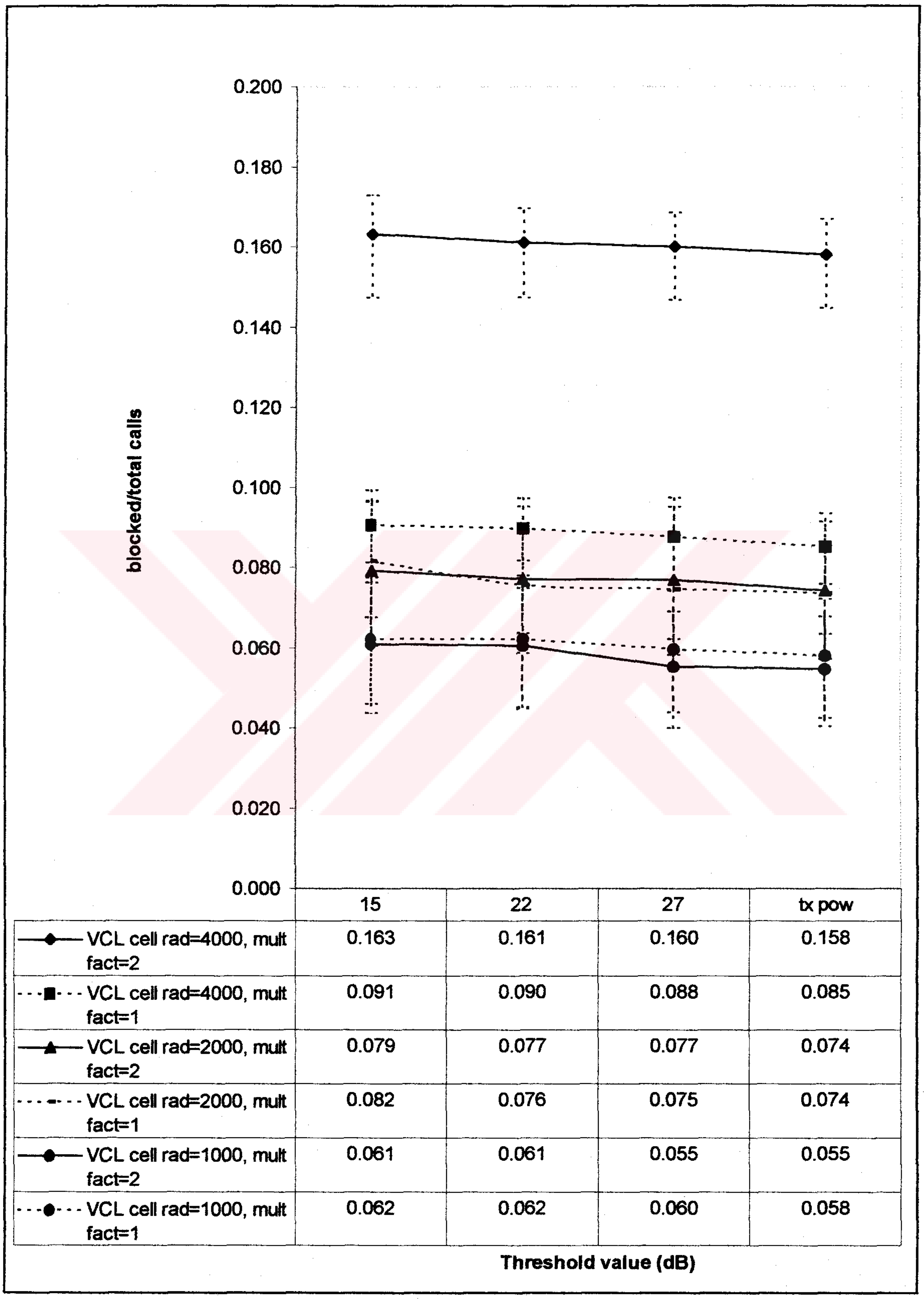
5.1. Analysis of Threshold Based Handoff Decision Algorithms

15 dB is chosen as the minimum acceptable signal level for components [35]. So at real cell boundaries, a mobile should receive 15 dB mean signal strength. RSS with 15 dB threshold means mobile does not think handing off to another access point while it receives an acceptable signal (above 15 dB) from its current access point. 22 dB corresponds to the mean signal strength received at 2/3 of the coverage area of the access point. That is with 22 dB threshold, the mobile does not think handing off to another access point while it is closer to its current access point more than 2/3 of the coverage distance of the access point. 27 dB corresponds to the mean signal strength received at 1/2 of the coverage area of the access point. That is with 27 dB threshold, the mobile does not think handing off to another access point while it is closer to its current access point more than 1/2 of the coverage distance of the access point.

Threshold based handoff decision algorithm shows degrading performance using the blocked calls due to lack of network resources to total calls ratio with the increasing VCL cell radius and the multiplication factor in Figure 5.1. Increasing the coverage area results in a higher transmission power for MPRs that are far from their access point which results in increasing interference and decreasing the soft capacity and increasing the number of blocked calls due to lack of network resources.

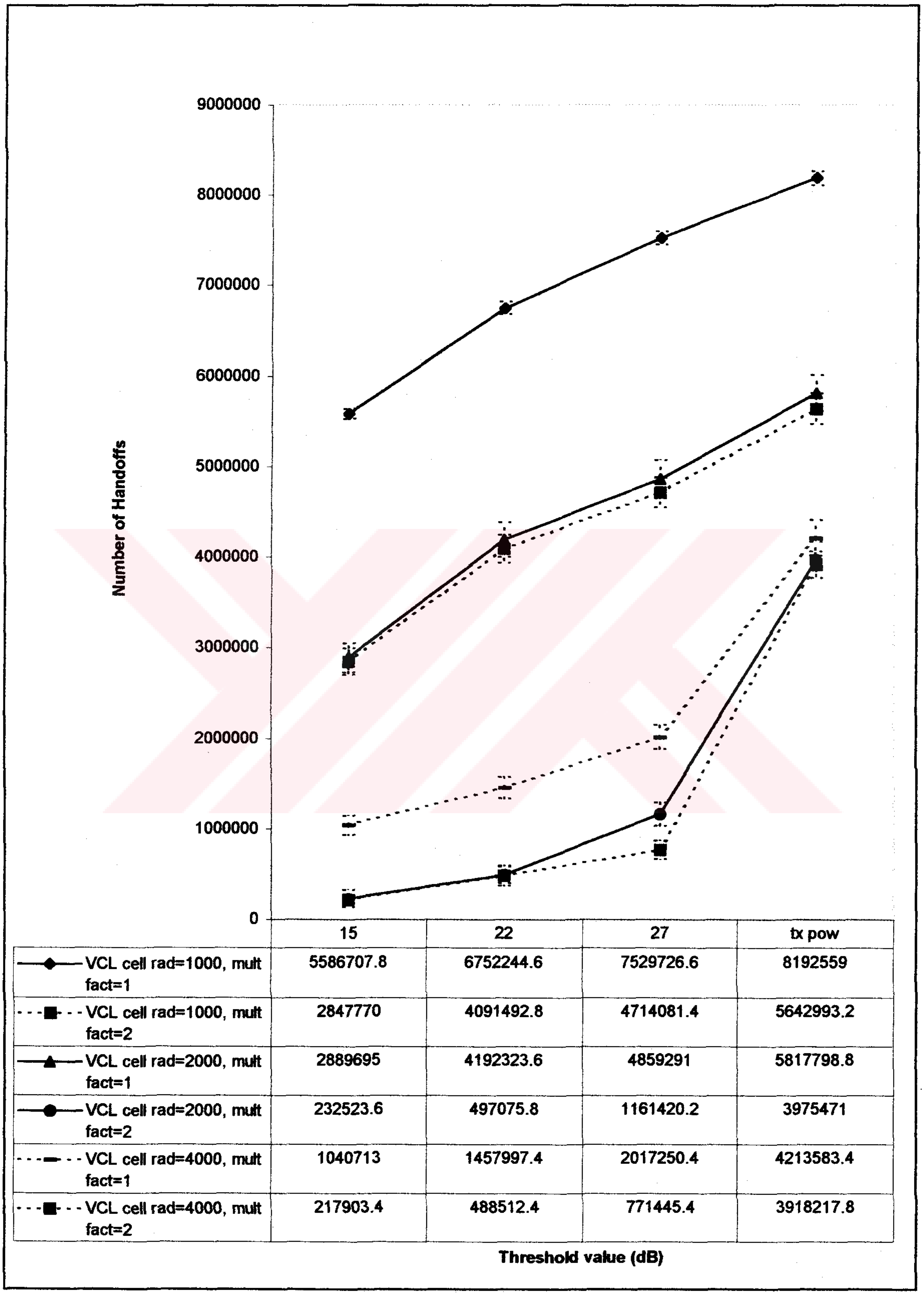
Increasing the coverage area results in less number of MPR handoffs in Figure 5.2. We were expecting more calls to be blocked due to lack of network resources with the increasing multiplication factor. However, we observe in Figure 5.1 that for VCL cell radius 1000 m, ratio of blocked calls due to lack of network resources decreases as we increase the multiplication factor from one to two. We can explain this with our call admission policy. We have no call prioritization in our simulation model. No guard channels are reserved for the handoffed calls in our access points. The result is increasing the number of blocked calls due to lack of network resources after a handoff. When we examine Figure 5.2 we see that number of MPR level handoffs are almost doubled when we decrease the multiplication factor from two to one for VCL cell radius of 1000 m. Increasing number of handoffs increases the probability of call blocking due to lack of network resources after a handoff. So, we have more calls blocked for the multiplication factor one with the VCL cell radius 1000 m. This situation may be avoided using more intelligent call admission policies with the cost of increasing the initial call blocking probability.

As the threshold for RSS with threshold algorithm increases, that is the mobile think handing off to another access point earlier, ratio of blocked calls due to lack of network resources to total calls decreases due to decreasing handoff delay. But the number of MPR level handoffs increases as the threshold increases. Figure 5.1 shows the Effect of threshold value on the ratio of blocked calls due to lack of network resources to total calls when multiplication factor is one and two. RSS algorithm has the most number of handoffs and the least ratio of blocked calls due to lack of network resources to total calls.



	15	22	27	tx pow
◆ VCL cell rad=4000, mult fact=2	0.163	0.161	0.160	0.158
■ VCL cell rad=4000, mult fact=1	0.091	0.090	0.088	0.085
▲ VCL cell rad=2000, mult fact=2	0.079	0.077	0.077	0.074
- VCL cell rad=2000, mult fact=1	0.082	0.076	0.075	0.074
● VCL cell rad=1000, mult fact=2	0.061	0.061	0.055	0.055
● VCL cell rad=1000, mult fact=1	0.062	0.062	0.060	0.058

Figure 5.1. Analysis of threshold based algorithms in terms of blocked calls due to lack of network resources



	15	22	27	tx pow
—◆— VCL cell rad=1000, mult fact=1	5586707.8	6752244.6	7529726.6	8192559
- - -■- - - VCL cell rad=1000, mult fact=2	2847770	4091492.8	4714081.4	5642993.2
—▲— VCL cell rad=2000, mult fact=1	2889695	4192323.6	4859291	5817798.8
—●— VCL cell rad=2000, mult fact=2	232523.6	497075.8	1161420.2	3975471
- - -▬- - - VCL cell rad=4000, mult fact=1	1040713	1457997.4	2017250.4	4213583.4
- - -■- - - VCL cell rad=4000, mult fact=2	217903.4	488512.4	771445.4	3918217.8

Threshold value (dB)

Figure 5.2. Analysis of threshold based algorithms in terms of the total number of MPR level handoffs

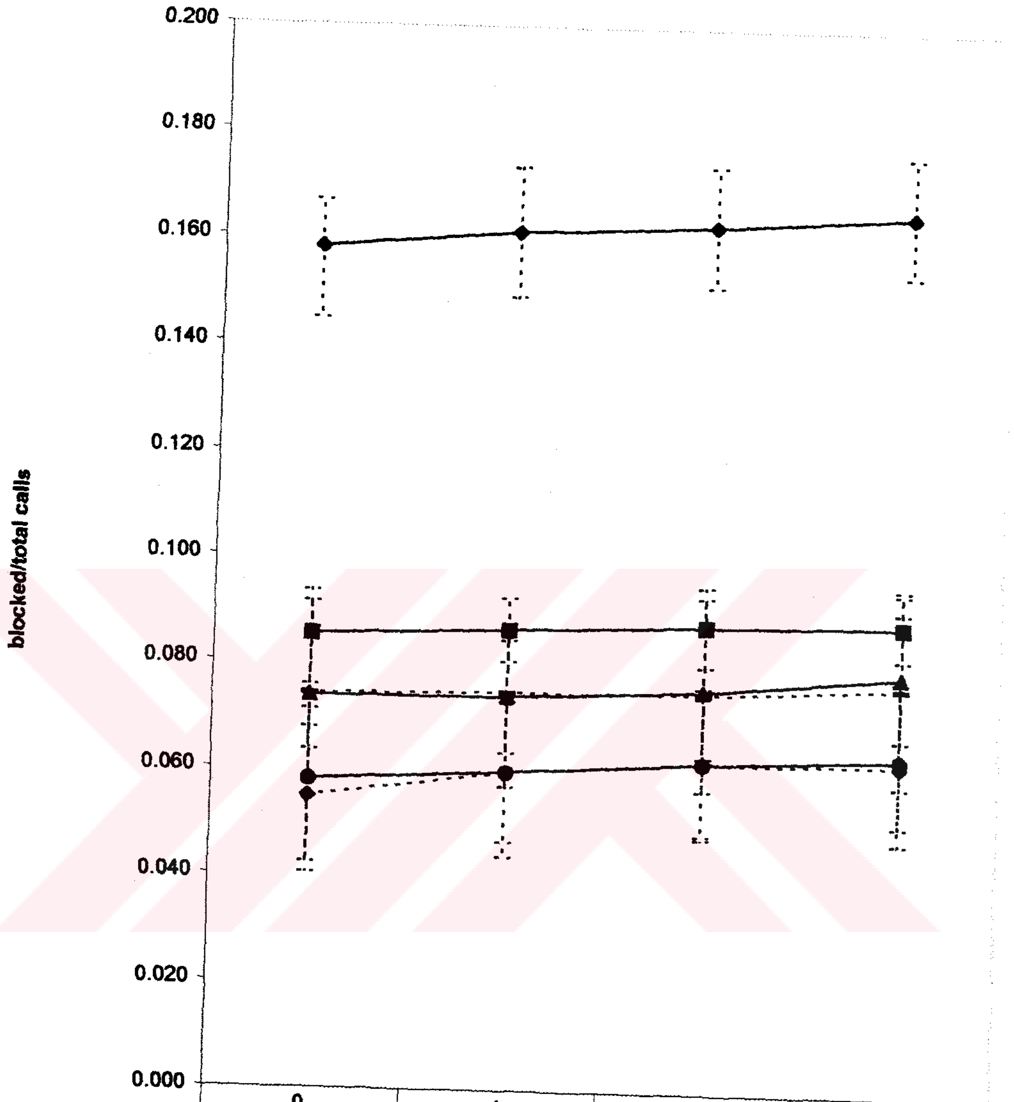
We can explain the situation as follows; With RSS algorithm, the mobile hands off to another access point whenever a better access point is available. Handoff delay is zero in this case but we suffer from the ping-pong effect. Figure 5.2 shows the effect of threshold value on the total number of MPR level handoffs when the multiplication factor is one and two.

5.2. Analysis of Hysteresis Based Handoff Decision Algorithms

The hysteresis value of zero means handoff to a better access point whenever exists. Increasing the hysteresis value causes the mobile to handoff to another access point if its signals are received an amount of hysteresis value better than the current access point. So, increasing the hysteresis introduces a delay to the handoff. The result is increased transmission power for power controlled systems, increased global interference, increased blocked calls due to lack of network resources. The total number of MPR level handoffs is highest when the hysteresis value is zero and as the hysteresis value increases total number of MPR level handoffs decreases. Effect of the VCL cell radius and the multiplication factor on the ratio of blocked calls due to lack of network resources to total calls and the total number of MPR level handoffs is the same with threshold based handoff decision algorithm. Increasing VCL radius or multiplication factor increases the cell coverage area, which results in higher transmission powers, and higher global interference level that causes more calls to be blocked due to lack of network resources, for an interference limited environment. Figure 5.3 shows the ratio of blocked calls due to lack of network resources to total calls for RSS with four dB hysteresis, RSS with eight dB hysteresis, and RSS with 12 dB hysteresis. Figure 5.4 shows the effect of the VCL cell radius and the multiplication factor on the total number of MPR level handoffs for RSS with four dB hysteresis, RSS with eight dB hysteresis, and RSS with 12 dB hysteresis. Increasing the coverage area reduces the total number of MPR level handoffs.

5.3. Analysis of Multicriteria Handoff Decision Algorithm

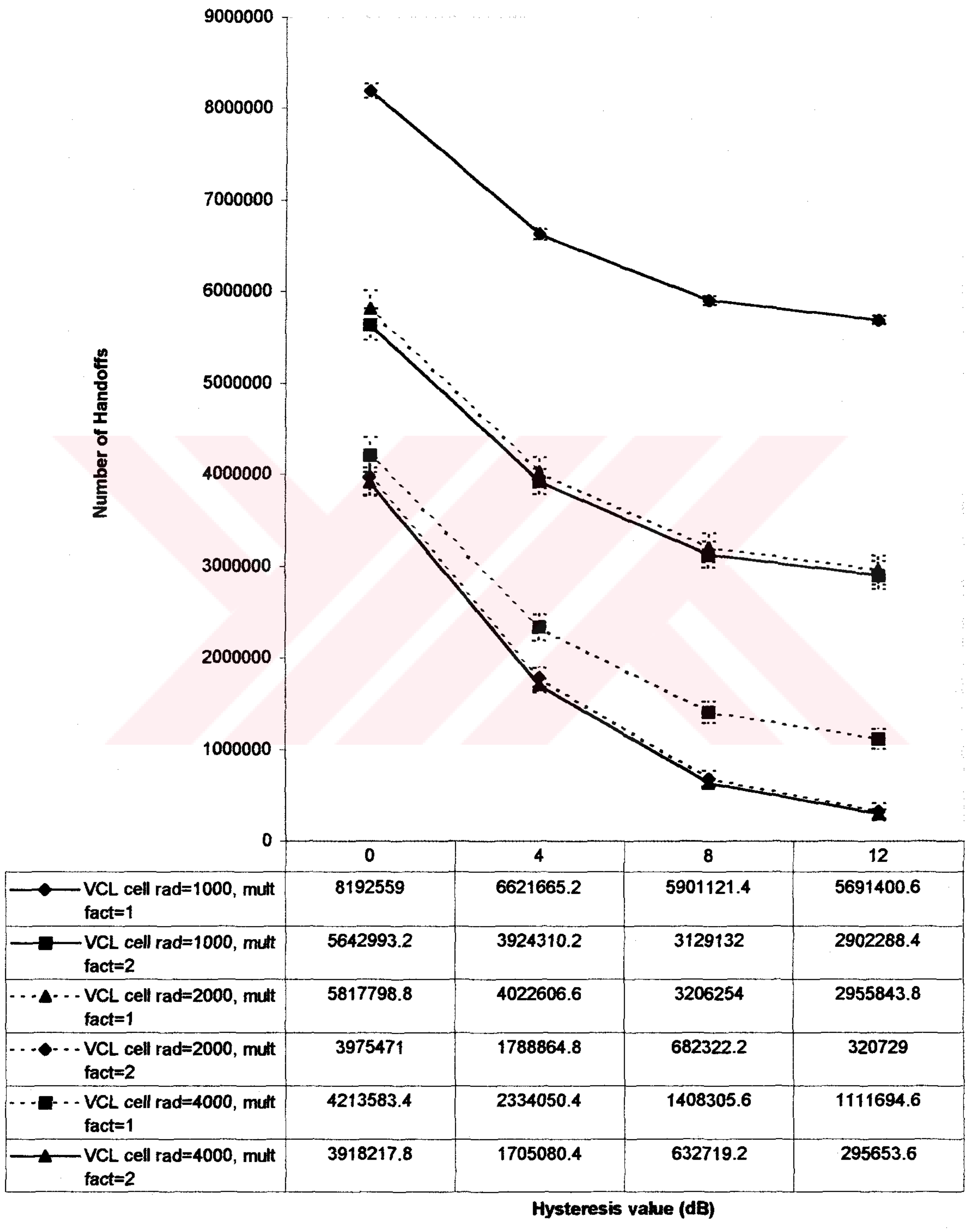
For Multi-criteria handoff decision algorithm, the membership value to an access point is between one and nine. Having a membership value threshold nine means that the mobile does not think handing off to another access point while its membership value to



	0	4	8	12
◆ VCL cell rad=4000, mult fact=2	0.158	0.161	0.163	0.165
■ VCL cell rad=4000, mult fact=1	0.085	0.086	0.088	0.088
- - - VCL cell rad=2000, mult fact=2	0.074	0.075	0.075	0.077
▲ VCL cell rad=2000, mult fact=1	0.074	0.074	0.075	0.079
- -◆- - VCL cell rad=1000, mult fact=2	0.055	0.060	0.062	0.062
● VCL cell rad=1000, mult fact=1	0.058	0.060	0.062	0.063

Hysteresis value (dB)

Figure 5.3. Analysis of hysteresis based algorithms in terms of blocked calls due to lack of network resources



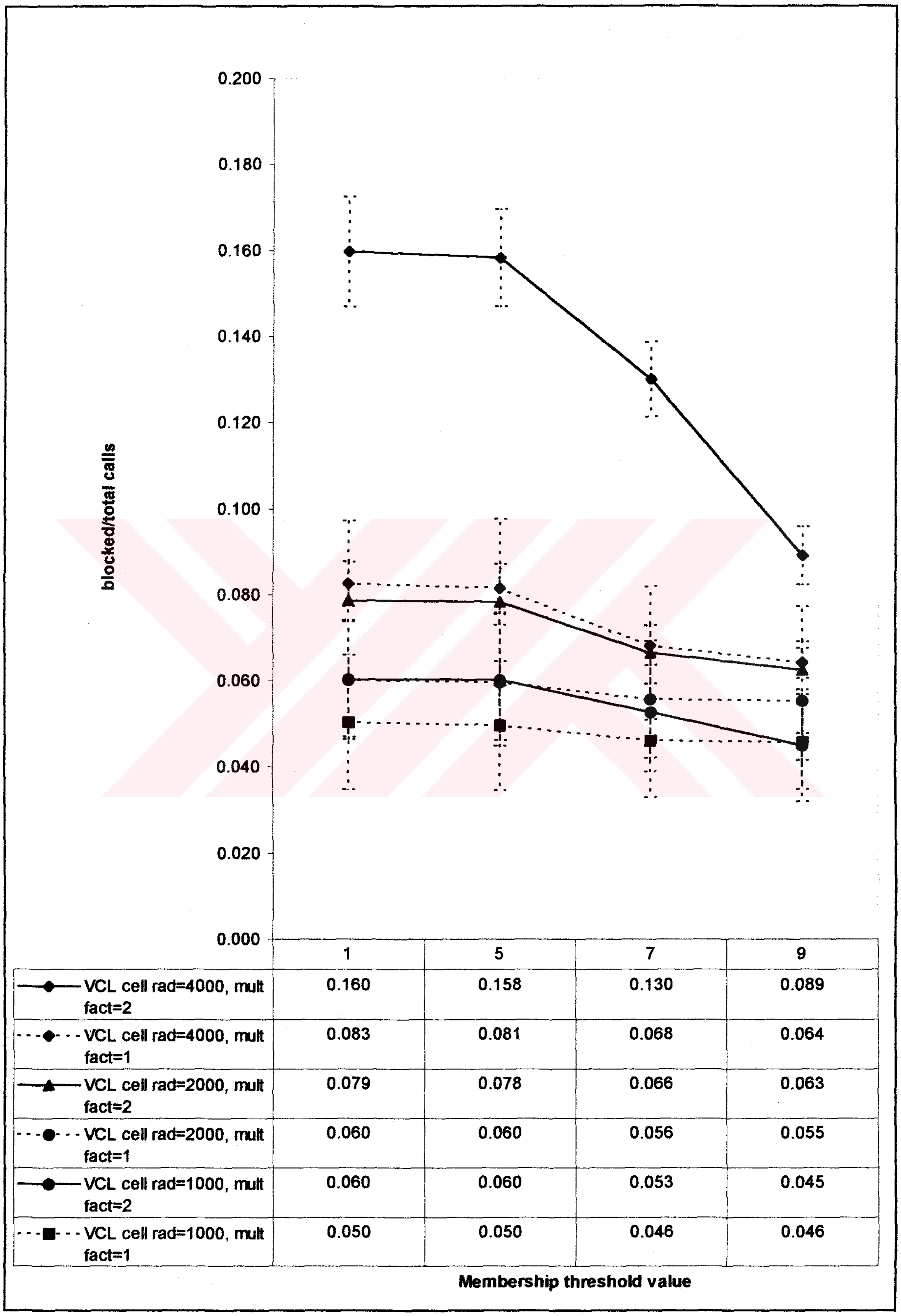
	0	4	8	12
—◆— VCL cell rad=1000, mult fact=1	8192559	6621665.2	5901121.4	5691400.6
—■— VCL cell rad=1000, mult fact=2	5642993.2	3924310.2	3129132	2902288.4
- - -▲- - - VCL cell rad=2000, mult fact=1	5817798.8	4022606.6	3206254	2955843.8
- - -◆- - - VCL cell rad=2000, mult fact=2	3975471	1788864.8	682322.2	320729
- - -■- - - VCL cell rad=4000, mult fact=1	4213583.4	2334050.4	1408305.6	1111694.6
—▲— VCL cell rad=4000, mult fact=2	3918217.8	1705080.4	632719.2	295653.6

Hysteresis value (dB)

Figure 5.4. Analysis of hystresis based algorithms in terms of the total number of MPR level handoffs

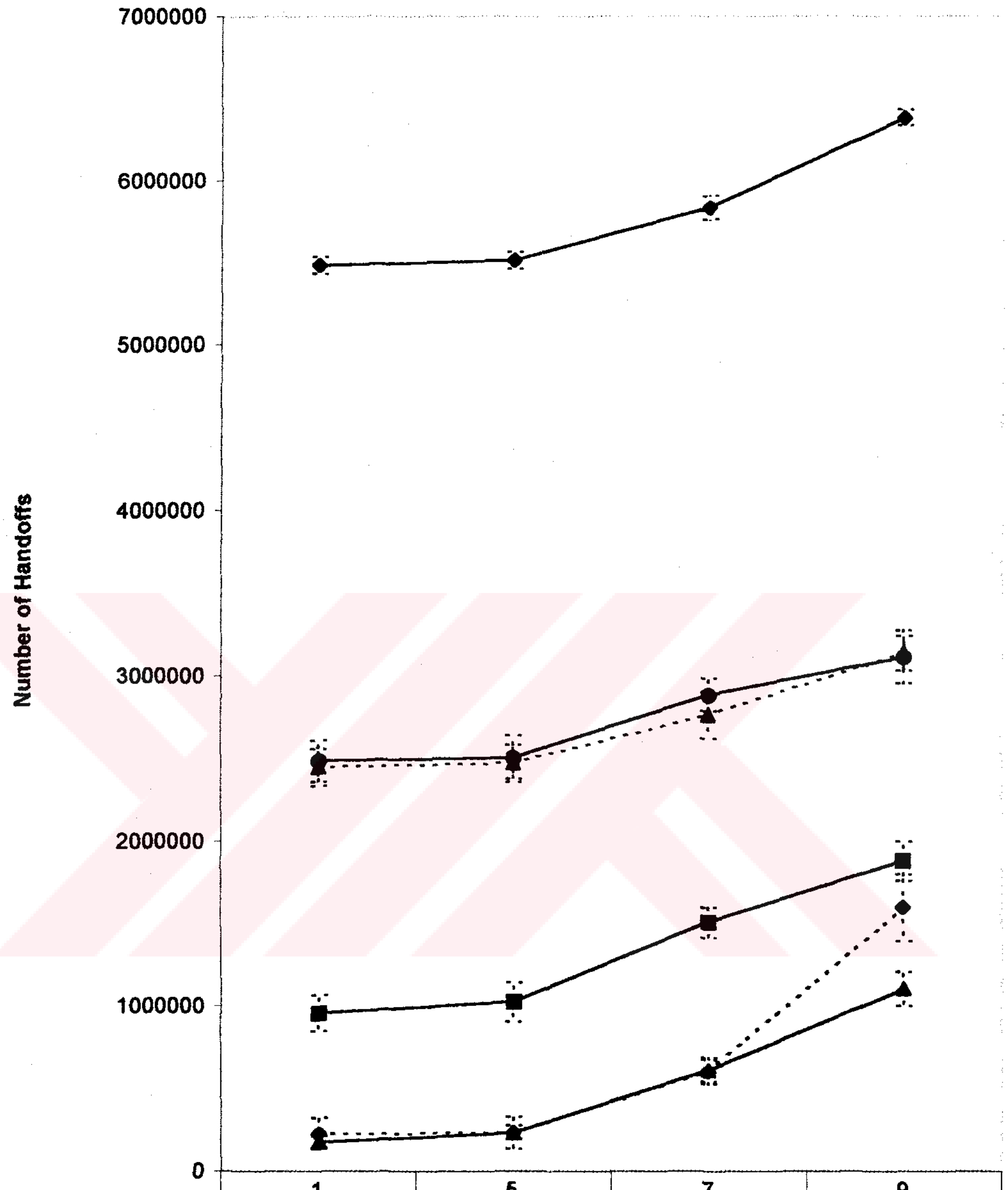
the current access point does not drop below nine. In other words, the mobile hands off immediately to an access point having better membership value than the current access point. Having a membership value threshold one means mobile does not think handing off to another access point while its membership value to the current access point does not drop below one. In other words, the mobile does not hand off to another access point while it is receiving acceptable signal strength from its current access point. As the coverage area increases, transmission power increases, global interference level increases and more calls get blocked due to lack of network resources. For RSS, RSS with threshold and RSS with hysteresis algorithms, small VCL radius and small multiplication factor, i.e. VCL cell radius 1000 m and multiplication factor one, more calls were blocked than expected because of the enormous increase in the total number of MPR level handoffs. This was explained with our call admission policy. Although we are using the same call admission policy for multicriteria handoff decision algorithm, increasing the multiplication factor from one to two for the VCL cell radius 1000 m results in more calls to be blocked due to lack of network resources. This is expected. With the multicriteria handoff decision algorithm, we are considering the state of the target access point of handoff. So access points with high traffic load are not likely to be handed off, which results in a reduction in the number of blocked calls due to lack of network resources after a handoff. As the coverage area increases less number of MPR level handoffs performed.

We provide a detailed examination of the effect of membership value threshold for the multicriteria handoff decision algorithm. Increasing the membership value threshold results with more number of MPR level handoffs and less handoff delay. However, less blocked calls due to lack of network resources. Increasing the membership value threshold reduces the global interference level. Figure 5.5 shows the effect of the membership value threshold on the ratio of blocked calls due to lack of network resources to total calls for different VCL cell radii and multiplication factors. As the membership value threshold increases, fewer calls get blocked due to lack of network resources because of the decreasing global interference level. Figure 5.6 shows the effect of the membership value threshold on the total number of MPR level handoffs for different VCL cell radiuses and multiplication factors. As the membership threshold value increases, number of handoffs increases because of the decreasing handoff decision delay.



	1	5	7	9
—◆— VCL cell rad=4000, mult fact=2	0.160	0.158	0.130	0.089
- - -◆- - - VCL cell rad=4000, mult fact=1	0.083	0.081	0.068	0.064
—▲— VCL cell rad=2000, mult fact=2	0.079	0.078	0.066	0.063
- - -●- - - VCL cell rad=2000, mult fact=1	0.060	0.060	0.056	0.055
—●— VCL cell rad=1000, mult fact=2	0.060	0.060	0.053	0.045
- - -■- - - VCL cell rad=1000, mult fact=1	0.050	0.050	0.046	0.046

Figure 5.5. Analysis MCHOA in terms of blocked calls due to lack of network resources



	1	5	7	9
—◆— VCL cell rad=1000, mult fact=1	5484380.8	5513589	5839465	6385707.8
- - ▲ - - VCL cell rad=1000, mult fact=2	2444112.2	2470001.2	2760391	3138535.2
—●— VCL cell rad=2000, mult fact=1	2482351.8	2506658.6	2884072.6	3115758.2
- - ◆ - - VCL cell rad=2000, mult fact=2	227756.4	234012.6	606685.8	1596579.2
—■— VCL cell rad=4000, mult fact=1	958371.4	1024352.6	1506702.2	1878444.4
—▲— VCL cell rad=4000, mult fact=2	175439	233357.6	607267.4	1105469.2

Membership threshold value

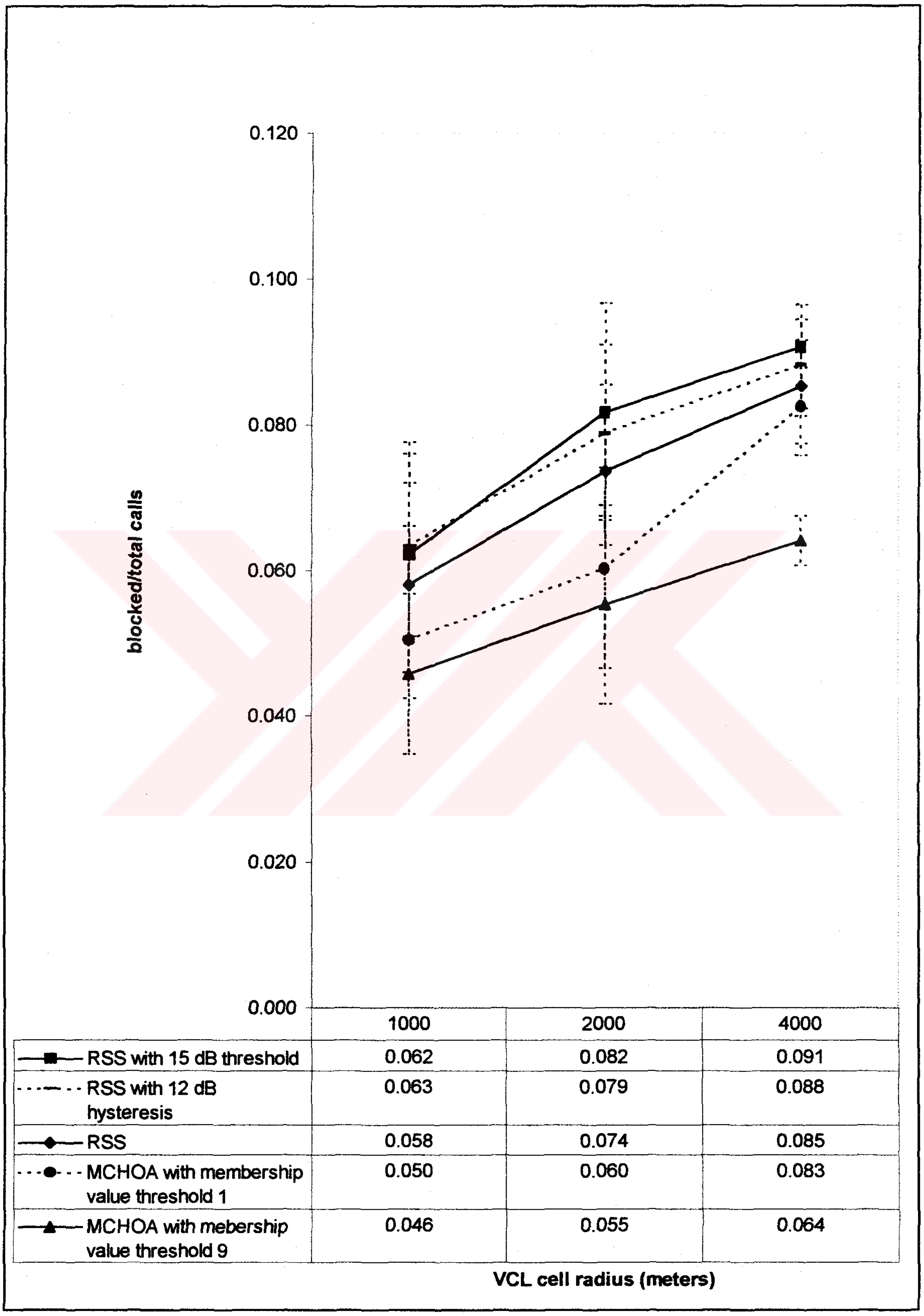
Figure 5.6. Analysis of MCHOA in terms of the total number of MPR level handoffs

5.4. Comparison of the Handoff Algorithms

We compared the proposed multicriteria handoff decision algorithm with the RSS based handoff algorithms according to the performance metrics of the blocked calls due to lack of network resources and the total number of MPR level handoffs. In Figure 5.7 when VCL cell radius is 4000 m, MCHOA with membership value threshold nine is better than the RSS algorithm in terms of blocked calls due to lack of network resources with the confidence of 95 per cent, since confidence intervals do not overlap. RSS algorithm was best in terms of blocked calls due to lack of network resources among RSS algorithm, RSS with threshold algorithm, RSS with hysteresis algorithm. When VCL cell radius is 2000 m, we see that the confidence intervals of the MHOA with membership value threshold 9 and RSS based handoff algorithm overlap. Hence the mean values are outside the rage of others confidence interval. So, we should perform a t-test [34] to decide if MCHOA with membership value threshold nine is better than the RSS based handoff algorithm with 95 per cent confidence for VCL cell radius 2000 m, and multiplication factor one. Result of the t-test is that MCHOA with membership value threshold nine is better than the RSS handoff decision algorithm with the 95 per cent confidence for VCL cell radius 2000 m and the multiplication factor one. When VCL cell radius is 1000 m, the mean value of the MCHOA with the membership value threshold nine is in the range of the RSS handoff algorithm's confidence interval. Although the mean value and the confidence intervals are better for MCHOA with membership value threshold nine is better than the RSS algorithm, there is no significant difference between them with 95 per cent confidence for VCL cell radius 1000 m and the multiplication factor one.

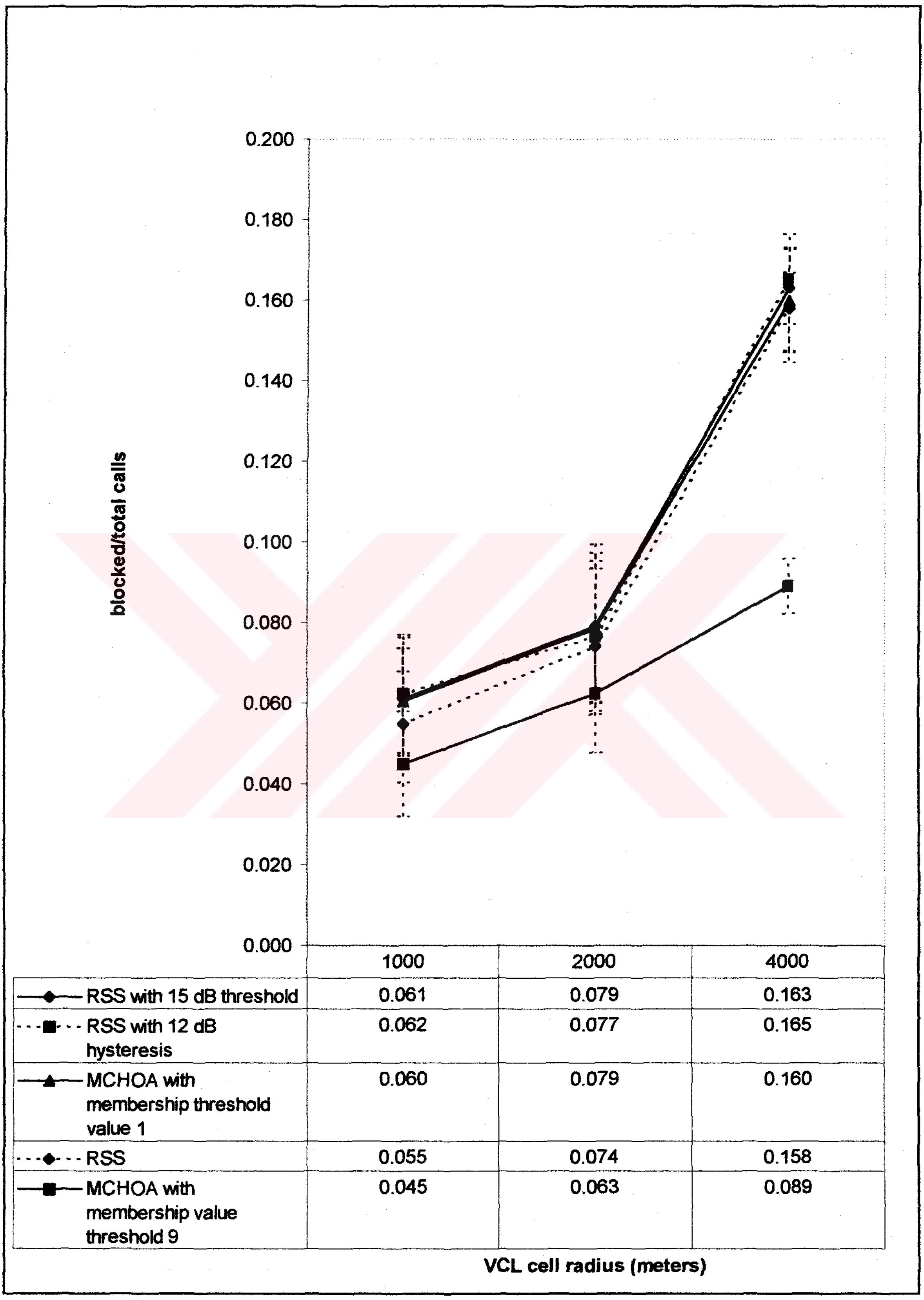
In Figure 5.8, we see that the MCHOA with membership value threshold nine is better than the RSS handoff decision algorithm with 95 per cent confidence when the VCL cell radius is 4000 m, for the multiplication factor two. Hence, there is no significant difference with 95 per cent confidence when VCL cell radius is 1000 m and 2000 m for the multiplication factor two.

In Figure 5.9 and Figure 5.10 we see that MCHOA with membership value threshold one, achieves the minimum number of handoffs among others with the confidence of 95 per cent.



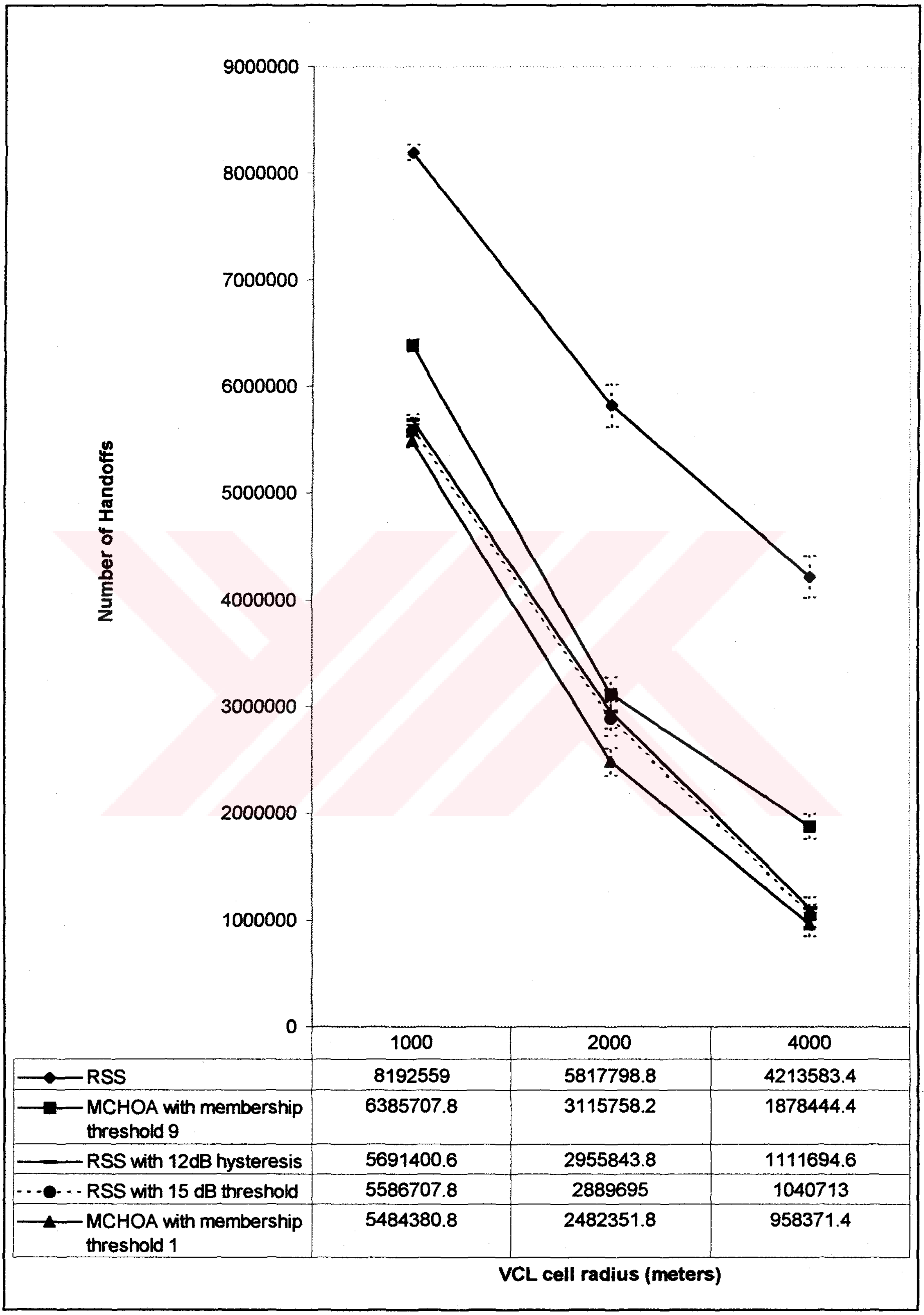
	1000	2000	4000
—■— RSS with 15 dB threshold	0.062	0.082	0.091
- - -— - - RSS with 12 dB hysteresis	0.063	0.079	0.088
—◆— RSS	0.058	0.074	0.085
- - -●- - - MCHOA with membership value threshold 1	0.050	0.060	0.083
—▲— MCHOA with mebership value threshold 9	0.046	0.055	0.064

Figure 5.7. Comparison of the handoff decision algorithms in terms of the blocked calls due to lack of network resources when the multiplication factor is one



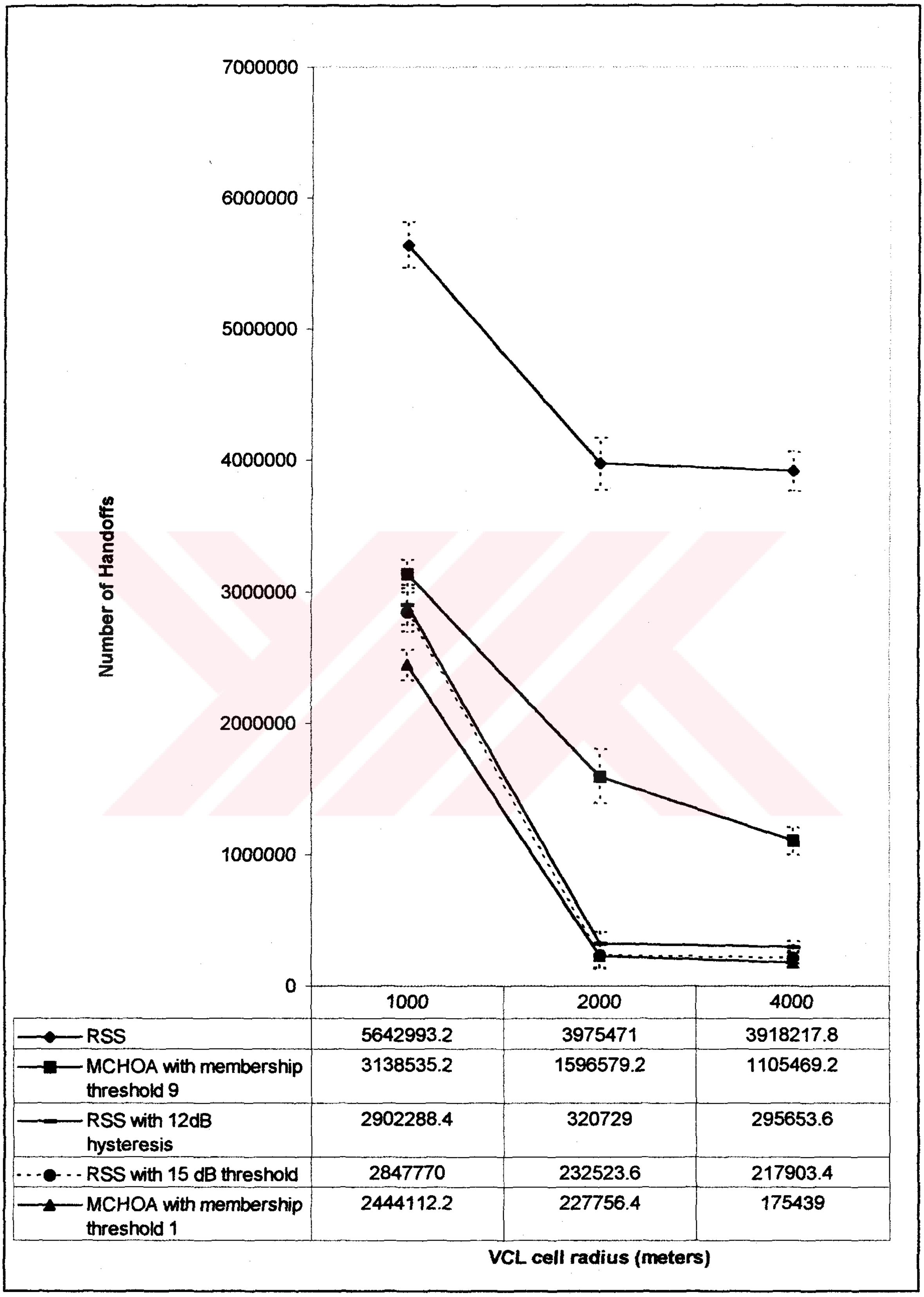
	1000	2000	4000
RSS with 15 dB threshold	0.061	0.079	0.163
RSS with 12 dB hysteresis	0.062	0.077	0.165
MCHOA with membership threshold value 1	0.060	0.079	0.160
RSS	0.055	0.074	0.158
MCHOA with membership value threshold 9	0.045	0.063	0.089

Figure 5.8. Comparison of the handoff decision algorithms in terms of the blocked calls due to lack of network resources when the multiplication factor is two



	1000	2000	4000
—◆— RSS	8192559	5817798.8	4213583.4
—■— MCHOA with membership threshold 9	6385707.8	3115758.2	1878444.4
—— RSS with 12dB hysteresis	5691400.6	2955843.8	1111694.6
- - -●- - - RSS with 15 dB threshold	5586707.8	2889695	1040713
—▲— MCHOA with membership threshold 1	5484380.8	2482351.8	958371.4

Figure 5.9. Comparison of the handoff decision algorithms in terms of the total number of MPR level handoffs when the multiplication factor is one



	1000	2000	4000
—◆— RSS	5642993.2	3975471	3918217.8
—■— MCHOA with membership threshold 9	3138535.2	1596579.2	1105469.2
—— RSS with 12dB hysteresis	2902288.4	320729	295653.6
- - -●- - - RSS with 15 dB threshold	2847770	232523.6	217903.4
—▲— MCHOA with membership threshold 1	2444112.2	227756.4	175439

VCL cell radius (meters)

Figure 5.10. Comparison of the handoff decision algorithms in terms of the total number of MPR level handoffs when the multiplication factor is two

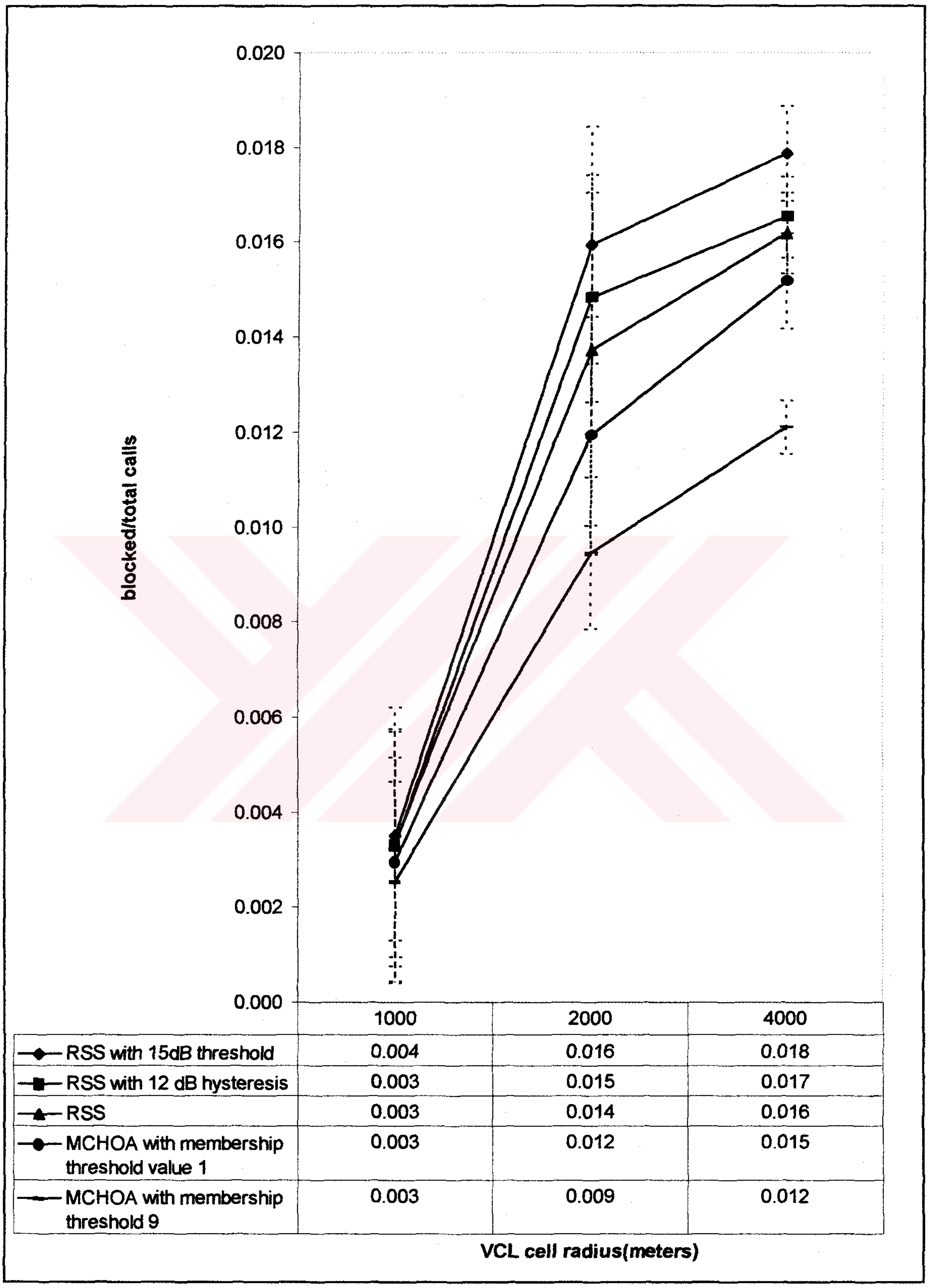
5.5. Different Scenario

We have done tests with another scenario, which has thirty minutes duration, 28 units, 3452 MPRs and 20 RAPs. Simulation area is 85 km x 40 km in size. From Figures 5.11 and Figure 5.12 we observe that as the VCL cell radius increases the blocked calls due to lack of network resources increases due to reasons explained in Section 5.4. Also we see that MCHOA performs better than the other algorithms in terms of blocked calls due to lack of network resources, as in the first scenario. Figure 5.13 and Figure 5.14 show that the increasing VCL cell radius decreases the number of handoffs with the same reasons explained in Section 5.4. We also observe that MCHOA with membership value threshold one has the least number of MPR level handoffs among other algorithms. These results comply with the results obtained from the first scenario. In Figures 5.11 and 5.14 the multiplication factor is taken one, and in Figures 5.12 and 5.14 the multiplication factor is taken as two.

5.6. Partial Effects of Handoff Decision Components

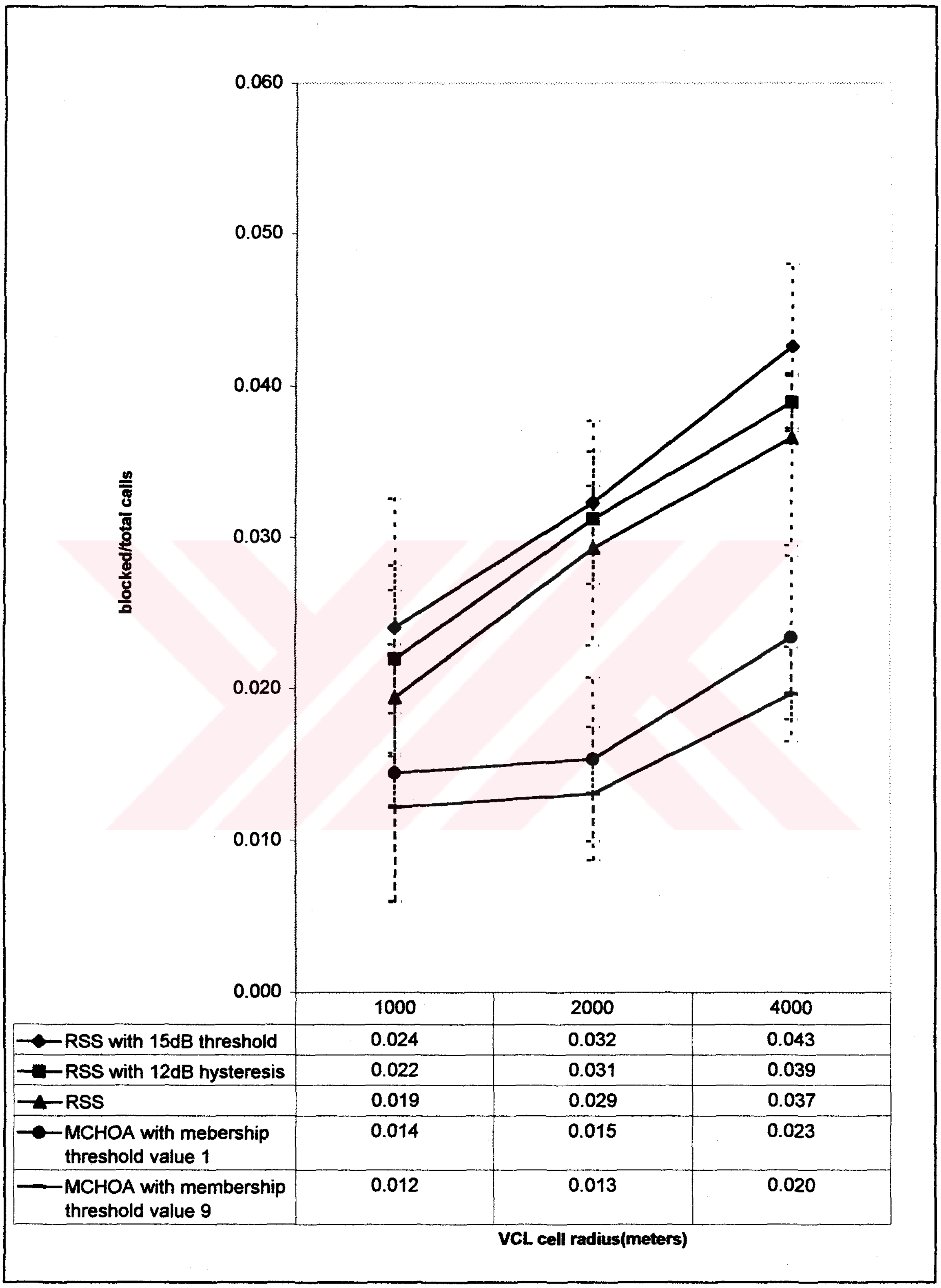
In this section, we examine the partial effects of the components employed in the multi-criteria handoff decision algorithm. Considering all four components, namely received signal strength from the access point, used soft capacity of the access point, relative direction and speed of the mobile to the access point. Employing fuzzy inference system yields our proposed multi-criteria handoff decision algorithm. When we consider only received signal strength from the access point, we employ the received signal strength based algorithm. Both algorithms mentioned above analyzed and compared in Section 5.1, Section 5.3, and Section 5.4 of this thesis for the first scenario and in Section 5.5 for the second scenario.

To examine how each component of the multi-criteria handoff decision algorithm affect on the ratio of blocked calls due to lack of network resources to total calls and the total number of MPR level handoffs, we investigated the case when virtual cell radius is 2000 m and the multiplication factor is two. We neutralize the affect of the relative speed and the relative direction and consider only received signal strength and the used soft capacity components.



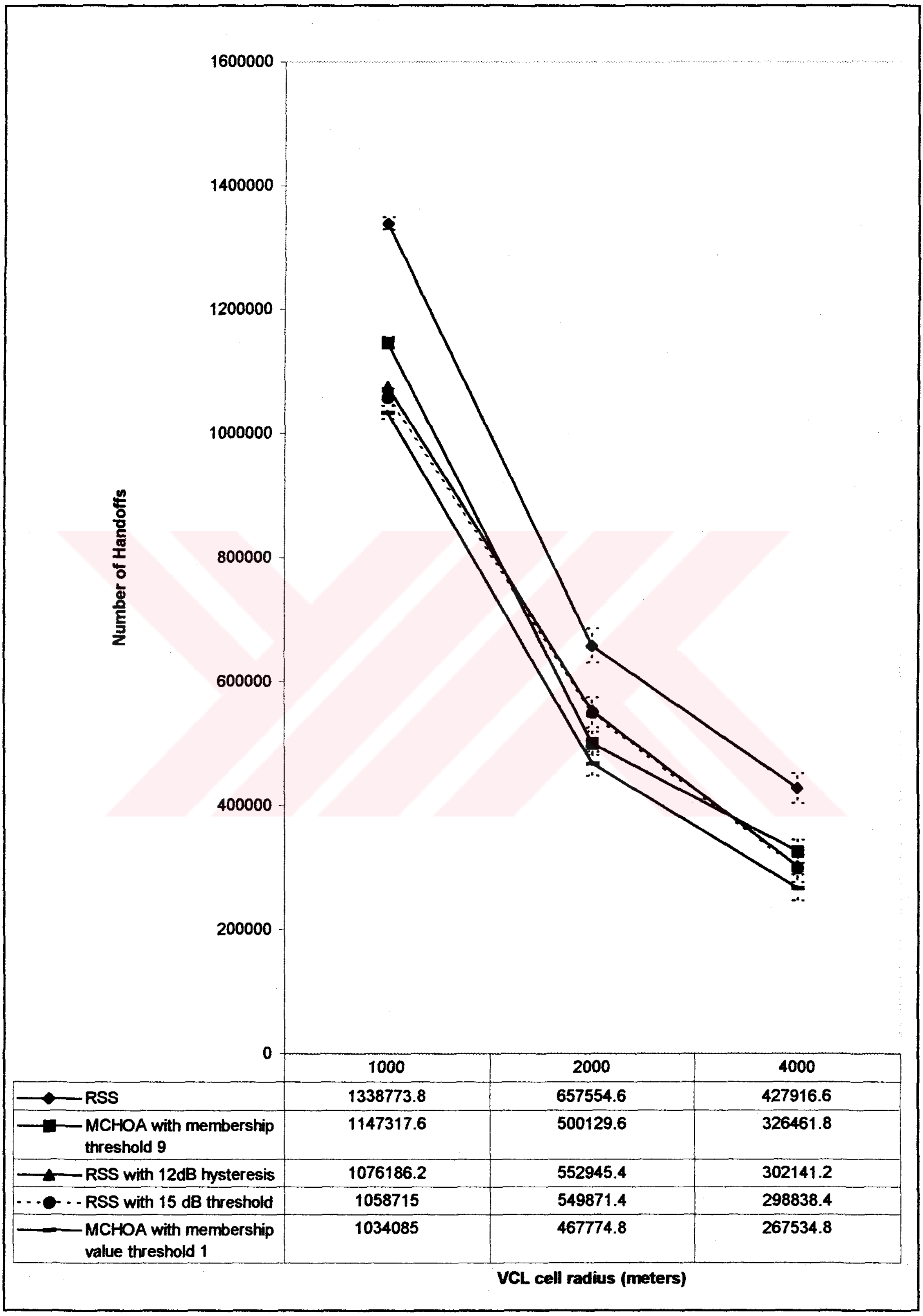
	1000	2000	4000
—◆— RSS with 15dB threshold	0.004	0.016	0.018
—■— RSS with 12 dB hysteresis	0.003	0.015	0.017
—▲— RSS	0.003	0.014	0.016
—●— MCHOA with membership threshold value 1	0.003	0.012	0.015
—— MCHOA with membership threshold 9	0.003	0.009	0.012

Figure 5.11. Comparison of the handoff decision algorithms for the second scenario, in terms of the blocked calls due to lack of network resources when the multiplication factor is one



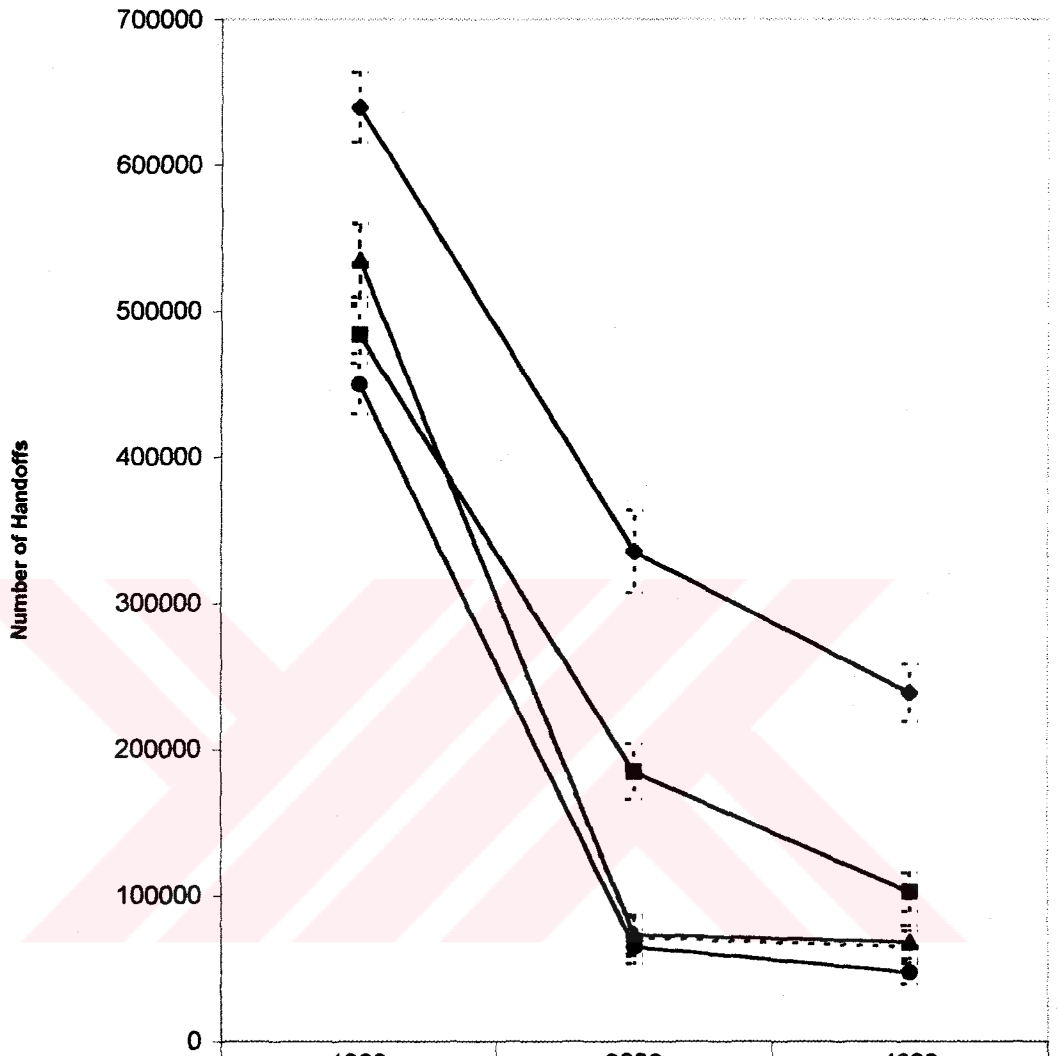
	1000	2000	4000
RSS with 15dB threshold	0.024	0.032	0.043
RSS with 12dB hysteresis	0.022	0.031	0.039
RSS	0.019	0.029	0.037
MCHOA with mebership threshold value 1	0.014	0.015	0.023
MCHOA with membership threshold value 9	0.012	0.013	0.020

Figure 5.12. Comparison of the handoff decision algorithms for the second scenario, in terms of the blocked calls due to lack of network resources when the multiplication factor is two



	1000	2000	4000
RSS	1338773.8	657554.6	427916.6
MCHOA with membership threshold 9	1147317.6	500129.6	326461.8
RSS with 12dB hysteresis	1076186.2	552945.4	302141.2
RSS with 15 dB threshold	1058715	549871.4	298838.4
MCHOA with membership value threshold 1	1034085	467774.8	267534.8

Figure 5.13. Comparison of the handoff decision algorithms for the second scenario, in terms of the total number of MPR level handoffs when the multiplication factor is one

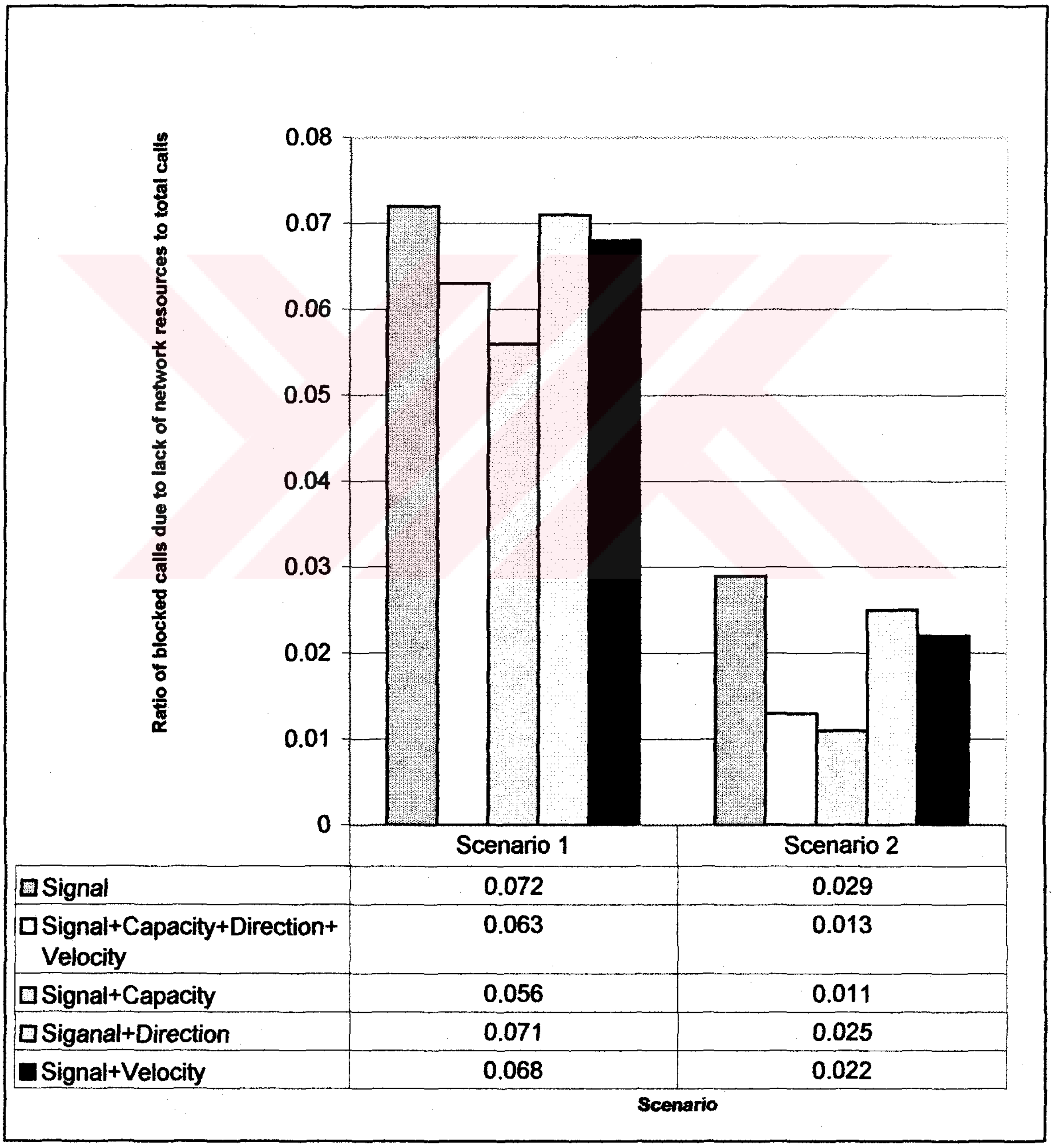


	1000	2000	4000
—◆— RSS	640041.8	335027.6	238431.4
—■— MCHOA with membership value threshold 9	483913	184616.4	102219
—▲— RSS with 12dB hysteresis	535090.2	72937.4	67796
- - ▬ - - RSS with 15 dB threshold	532572.6	71242.6	64557.2
—●— MCHOA with membership value threshold 1	450295.6	64742	47121

VCL cell radius(meters)

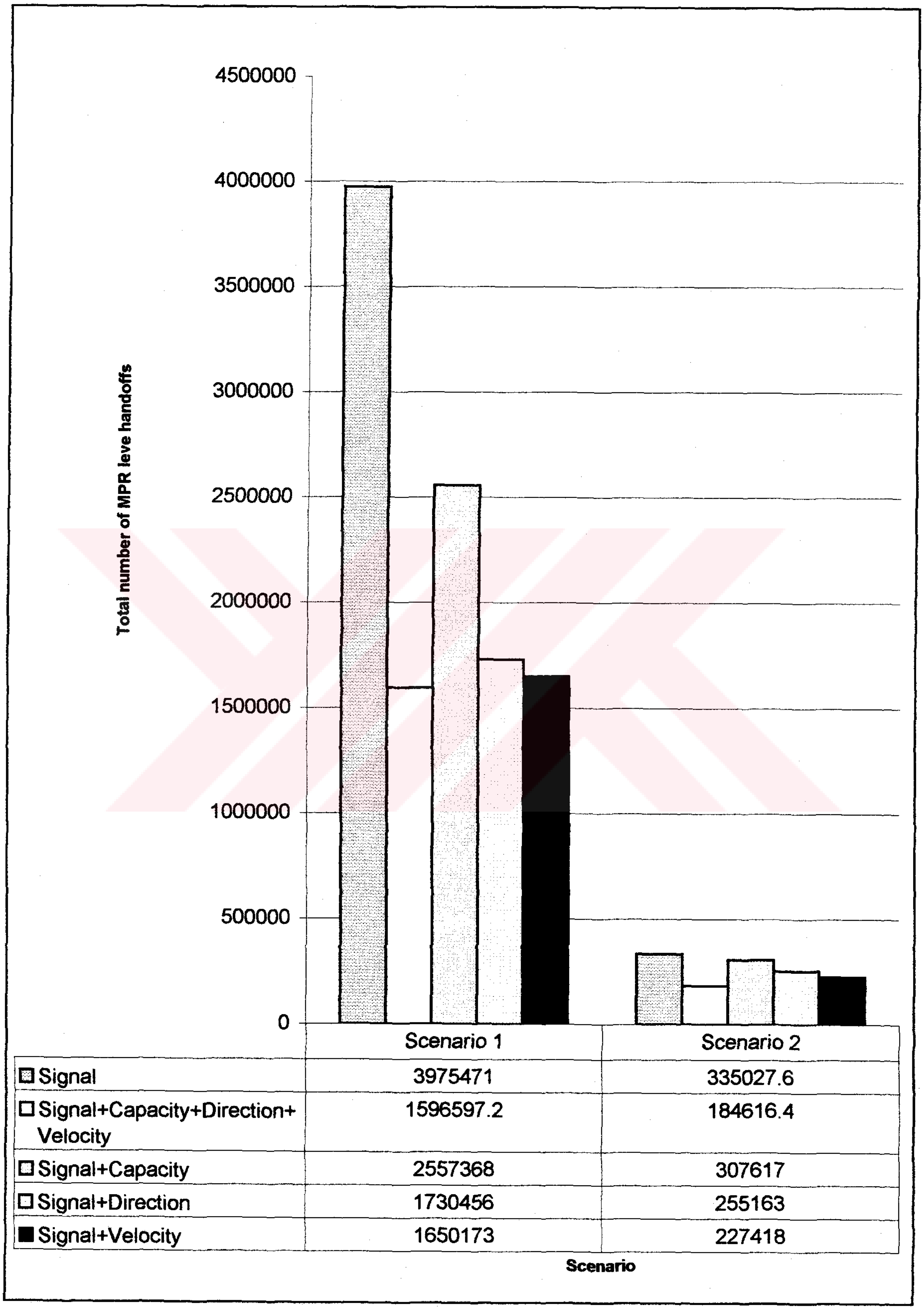
Figure 5.14. Comparison of the handoff decision algorithms for the second scenario, in terms of the total number of MPR level handoffs when the multiplication factor is two

We observe in Figure 5.15, that we achieve the least ratio of blocked calls to total calls when soft capacity and the received signal strength are used as the decision components. However, the penalty is increased number of handoffs as seen in Figure 5.16. Results obtained from first and second scenario are compatible. We have better performance when we consider relative speed with the received signal strength compared to the case in which relative direction and received signal strength is considered.



	Scenario 1	Scenario 2
▨ Signal	0.072	0.029
☐ Signal+Capacity+Direction+ Velocity	0.063	0.013
☐ Signal+Capacity	0.056	0.011
☐ Siganal+Direction	0.071	0.025
■ Signal+Velocity	0.068	0.022

Figure 5.15. Partial effect of the handoff decision components on the ratio of blocked calls due to lack of network resources to total calls



	Scenario 1	Scenario 2
▨ Signal	3975471	335027.6
☐ Signal+Capacity+Direction+ Velocity	1596597.2	184616.4
☐ Signal+Capacity	2557368	307617
☐ Signal+Direction	1730456	255163
■ Signal+Velocity	1650173	227418

Figure 5.16. Partial effect of the handoff decision components on the total number of MPR level handoffs

6. CONCLUSION

For mobile communication networks, the handoff delay and the number of handoffs are two conflicting design criteria. Increasing the handoff delay causes increased global interference level that yields decreased system capacity. Decreasing handoff delay causes increased number of handoffs. Since each handoff has a cost to the network we do not want a large number of handoffs.

We proposed a handoff decision algorithm based on the classification of fuzzy input variables for networks having a mobile infrastructure. We have tested our algorithm with a military network architecture having a mobile infrastructure [4] and compared the results with the other handoff decision algorithms.

In most cases, our algorithm achieved better grade of service and the total number of handoffs than other algorithms with 95 per cent confidence.

We test our algorithm with the membership threshold values one through nine. We see that with membership value threshold one we achieve minimum number of handoffs, and acceptable blocked call ratio. So we recommend one as membership value threshold for generic cases with our algorithm.

Among the handoff decision criteria used in the proposed algorithm, used soft capacity of the access point has the most effect on the blocked call ratio due to lack of network resources. Moreover, relative speed has more effect than the relative direction.

6.1. Future Work

Proposed multicriteria handoff decision algorithm can be applied to the mobile systems having immobile infrastructure with slight modifications.

Membership functions used in the fuzzifier are triangular and trapezoid. Other membership functions like Gaussian may be implemented and tested.

More intelligent call admission policies for the VCL architecture may be tested. One candidate algorithm, which can be applied, is proposed in [38] which is a hierarchical neuro-fuzzy call admission controller.

Adaptive fuzzy systems adjusting the parameters of the membership functions may be tested.

In our proposed handoff decision algorithm we assume that the access points broadcasting their speed, direction, total and used soft capacities. Mobile collects these metrics together with the received signal strength from the access points in the vicinity. And proposed algorithm runs on the mobile entity. The cost of broadcasting these metrics in the link level can be examined. In the handoff method using mobile location information proposed in [39] location request is done only when the handoff condition is triggered.

We use three fuzzy sets for input fuzzy variables. Increasing the number of fuzzy sets for input fuzzy variables can be considered with the penalty of increasing number of rules in the rule base. However, there are schemas proposed to eliminate redundant rules in the rule base [40].

In this thesis we examine only the total number of MPR level handoffs. We also provide a guideline for the MPR level handoff types that may take place in the VCL architecture. The MPR level handoffs from type 1 through type 4 are described in Section 3.2. Number of MPR level handoffs may be examined according to their type.

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