A MULTICRITERIA HANDOFF DECISION SCHEME FOR THE NEXT GENERATION TACTICAL COMMUNICATIONS SYSTEMS

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ABSTRACT

In this paper a novel handoff decision algorithm for the mobile subsystem of tactical communications systems is introduced. In this algorithm, handoff decision metrics are: received signal strength measurements from the access points, the ratio of the used capacity to the total capacity for the access points, and relative directions and speeds of the mobiles to the access points. We use a fuzzy inference system to process these metrics. We also introduce a " membership value" to represent the degree of membership of a mobile to an access point and "membership value threshold" to represent the minimum membership value before a mobile considers handing off to another access point. We compare our algorithm with the received signal strength based handoff decision algorithms. Our tests have shown that the proposed scheme, with the lowest membership value threshold, achieves the minimum number of handoffs, and the proposed scheme with the highest membership value threshold achieves the minimum call blocking rate.

I. INTRODUCTION

Mobile communications systems should use limited resources in an efficient and convenient manner. One way of achieving this is to use smaller cells at the expense of corresponding handoff and administration overhead. Many handoff algorithms proposed in the literature are classified according to the metrics used to decide whether a handoff is necessary or not, where these metrics are monitored, and how these metrics are processed. Some of the metrics proposed are; signal strength [1], distance [2], signal to noise ratio [3], bit error rate [4], traffic load [5], word error indicator [6], quality indicator [6], and some combination of these [6,7]. Metrics can be measured and processed on the network entity or on the mobile. There are several handoff decision algorithms that employ tools of artificial intelligence like fuzzy logic systems [8-11], neural networks [8,12], and pattern recognition algorithms [8,13-15] to process the collected metrics.

The Received Signal Strength (RSS) based handoff algorithm associates mobile host to the access point, which has the strongest perceived signal strength at the mobile host side. The signal received from an access point degrades as the distance between the mobile and the access point increases. However, this degradation is a random process due to uncertainties in the propagation environment. Around mid-point between two access points, the difference in the signal strengths received from access point 1 and access point 2 oscillates and the mobile may handoff several times between access point 1 and access point 2. This is called the ping-pong effect. To remedy the ping-pong effect, a threshold is introduced to the received signal strength based handoff algorithm [16]. The mobile does not hand off as long as the received signal strength from the currently serving access point does not drop below the predetermined threshold level. This algorithm is called Absolute Signal Strength algorithm [8]. Another technique is to introduce a hysteresis to the RSS algorithm [16]. The mobile does not hand off to another access point while the received signal strength from the candidate access point is not better an amount of predetermined hysteresis level than the received signal strength of the currently serving access point. This algorithm is called Relative Signal Strength algorithm [8]. Introducing both hysteresis and threshold is called the combined absolute and relative signal strength algorithm [8]. Either introducing hysteresis or threshold reduces the ping-pong effect but introduces a delay to the handoff, i.e., handoff is done later than it is expected. Effects of delaying handoff are increased interference, lower grade of service, i.e., call blocking and dropping rates. 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 access points [2,7]. In the design of handoff algorithms, there is an inherent trade off in timeliness and accuracy. The algorithms, which we explained thus far, were signal strength based algorithms. Another category is the distance-based algorithms. Distance-based algorithms relate the mobile with the closest access point [2]. The relative distance measurements can be obtained by comparing propagation delay times. Velocity adaptive handoff algorithms consider mobiles with different velocities, i.e., the handoff needs of fast moving mobiles should be determined immediately. This can be achieved by adjusting the effective length of the averaging window in which received signal strengths from the access point are averaged [7]. In direction biased algorithms handoffs to the access points towards which the mobile is moving are encouraged, while handoffs to the access points from which the mobile is receding are discouraged [8]. In pre-selection handoff algorithm, a mobile hands off to the access point towards which the mobile is moving even though measured handoff decision metrics of that access point are not the best, considering that these metrics will improve as the mobile gets closer to the access point.

For multicriteria handoff, different pattern recognition based handoff decision algorithms have been proposed in the literature [8, 13-15]. 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 actually pre-training the system. However, when the system is trained, we have the opportunity to employ multicriteria algorithms and optimizing the handoff decision with conflicting criteria, i.e., handoff delay and number of handoffs.

In our new handoff decision algorithm, the handoff decision metrics are received signal strengths from the current and candidate access points, ratio of the used capacity to the total capacity for the access points, relative directions and speeds of the mobiles to the access points. We use a fuzzy inference system to process these metrics. The output of our fuzzy inference system is the membership value of a mobile for the currently registered and candidate access points, which is a real number between one and nine. We introduce a membership value threshold to trigger the handoff decision algorithm, i.e., the mobile does not handoff while its membership value to its current access point is above a predetermined membership threshold. If a handoff is necessary, the access point with the mobile's highest membership value is the target for the 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 level achieves minimum call blocking rate, and setting the membership value threshold to the lowest achieves the minimum number of handoffs. So our new handoff decision algorithm also provides an optimization tool based on two conflicting parameters, namely the number of handoffs and the call blocking rate.

Our handoff scheme is developed and tested for the virtual cell layout (VCL) based mobile subsystems of the tactical communications systems. In Section 2, the VCL based mobile subsystem is introduced. In Section 3, we explain our new handoff decision algorithm for the cellular networks with a mobile infrastructure. Experimental results for the proposed system are given in Section 4. We conclude our paper in Section 5.

II. THE VCL BASED MOBILE SUBSYSTEM FOR TACTICAL COMMUNICATIONS

The next generation tactical communications systems will provide digital battlefield forces with an efficient, robust, flexible, and tailorable network that can convey multimedia traffic. Figure 1 illustrates the architecture of the next generation tactical communications systems [17]. This architecture has four subsystems: The Local Area Subsystem (LAS), the Wide Area Subsystem (WAS), the Mobile Subsystem (MS), and the System Management and Control Subsystem (SMCS). A security system is also integrated into the architecture.

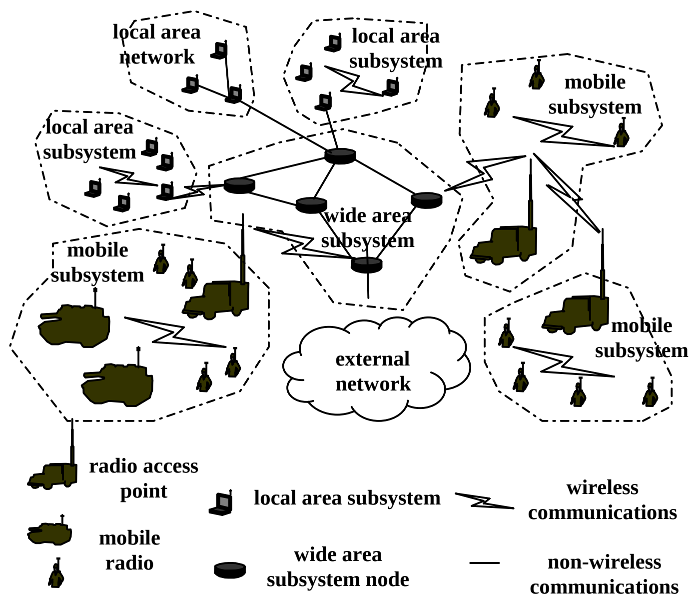

Figure 1. Tactical communications systems [17].

Cayirci and Ersoy propose a novel resource management technique, namely virtual cell layout (VCL) for the mobile subsystem of the next generation tactical communications systems [17]. Architectural elements of the system proposed in [17] are; man packed radios (MPR), radio access points (RAP), unmanned aerial vehicles (UAV), and satellites. Figure 2 illustrates the architectural elements of the multi-tier mobile subsystem. MPRs are mobile terminals with the additional capability of being an access point (AP) when needed. MPRs access to the WAS by means of an RAP. When no RAP is found in the vicinity, VCL helps MPRs to be clustered among them. RAPs can be thought as base stations. However, the difference is that they are mobile to satisfy the rapid deployment and survivability requirements. RAPs constitute the mobile infrastructure of the MS. UAVs and satellites provide an overlay architecture for the MS.

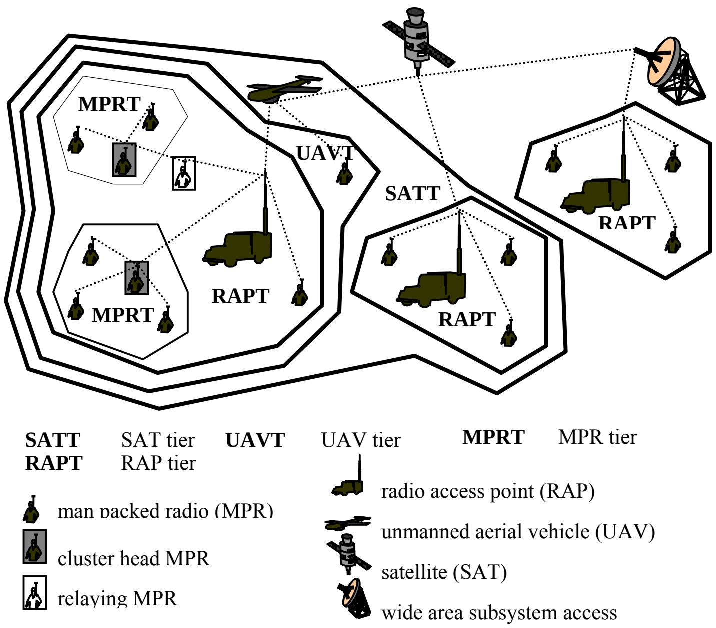

Figure 2. Architectural elements of the mobile subsystem [17].

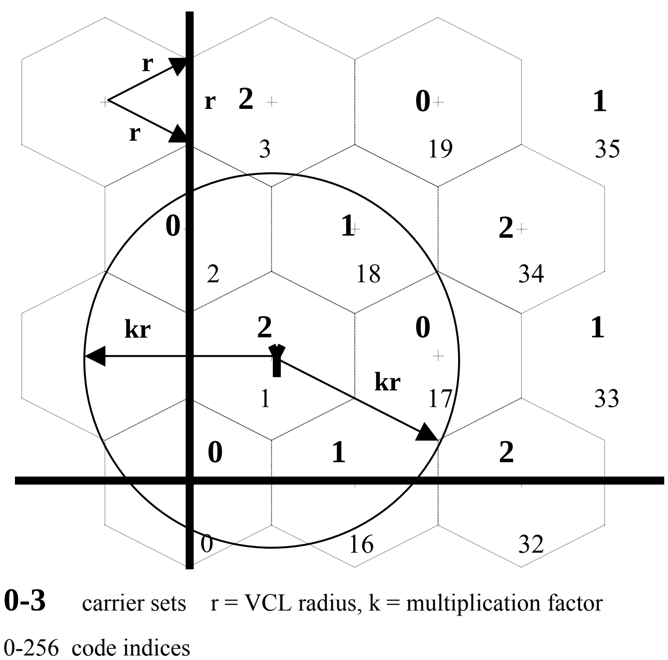

Figure 3. Virtual cell layout [17].

In the VCL based architecture, radio resources (i.e., frequency carriers and CDMA codes) are dynamically assigned to the components of a mobile infrastructure by using a VCL, which eliminates the need for a central system or an accurate and timely topology database. In VCL, the communication area is tessellated with virtual cells, which are regularly shaped fixed size hexagons that are placed starting from a reference geographic location. If an access point knows its geographic location, this location information can be mapped into a unique identifier, the VCL cell index, which can be used to determine the radio resources assigned to the fixed cells of VCL.

The real cells are mobile and created by either RAPs or cluster head MPRs (i.e., MPRT cell heads). The size of a real cell may be different from the size of a VCL cell. If a VCL cell radius is *r*, then the real cell radius is *kr*, $k \in R^+$, where *k* is a *multiplication factor*. When the multiplication factor is one, a real cell usually does not cover the entire virtual cell where it is located, because the access points are not necessarily at the centers of the virtual cells.

The carrier frequency set consists of a group of carriers. The frequency band allocated to this system is divided into carriers that have bandwidths between 4.4 and 5 MHz as in UMTS. These carriers are divided into three carrier sets, and each VCL cell is assigned a carrier set according to *N*=3 fixed frequency reuse plan as illustrated in Figure 3. *N=3* frequency reuse plan is proposed, since it is the one with the highest frequency reuse that ensures that none of the VCL cells has a neighbor VCL cell using the same carrier set. Although CDMA is used in this mobile subsystem, the same carrier set is not assigned in the neighboring cells because RAPs are mobile, and two RAPs can come too close to use the same frequency carrier even if they are in separate VCL cells. Please note that other multiple access schemes, e.g., TDMA and FDMA, can also be used with VCL.

UMTS uses 512 CDMA codes for identifying base stations [4]. These codes are divided into two groups of 256 codes. RAPs use the first 256 codes, and MPRs use the rest. Two codes are assigned to each VCL cell; one for RAPs and one for the MPR cluster heads. This implies that 256 code sets are distributed among the VCL cells as illustrated in Figure 3.

If a component can find out its geographic location, it can learn the most appropriate CDMA code and carrier set without the need for a central system or a database. Global Positioning System (GPS) based or GPS-less location finding techniques [18, 19] can be used to learn the current geographic location.

Fault tolerant self organization algorithms for RAPs and MPRs are explained in detail in [17] where the factors influencing the design of such a system, e.g., the VCL cell size, the multiplication factor, various classes of traffic, are also examined though extensive experiments. Realistic call, mobility and availability patterns obtained from the real computer assisted exercises are used to evaluate the performance of the proposed system [17]. The results of these experiments prove that the proposed VCL based mobile subsystem fulfills the requirements of a next generation tactical communications systems, such as high grade of service rates, rapid deployment, survivability, mobility, and the ability to transport bursty multimedia traffic.

In a military operation, we can expect that the mobiles usually move together with their access points. If a mobile executes a handoff solely on detection of a stronger emission from another access point, it may need another handoff to its former access point soon. In the Virtual Cell Layout (VCL) proposal [17] for the mobile subsystem of the tactical communications systems, the handoff decision algorithm is based on the received signal strength measurements with threshold. To keep the number of unnecessary handoffs at minimum, mobiles do not hand off to another access point while the received signal strength from the current access point is adequate to carry on the communication. Since the access points, i.e., RAPs and the cluster head MPRs, are mobile and expected to move together with mobile terminals, i.e., MPRs, this algorithm reduces the number of unnecessary handoffs. However, this algorithm results in increasing global interference levels, henceforth call blocking rates. Therefore, we introduce a more sophisticated handoff decision algorithm that takes into account both the number of handoffs and the global interference level.

III. THE FUZZY INFERENCE SYSTEM FOR HANDOFF DECISION

Sophisticated handoff decision algorithms should consider more than one handoff decision criteria and a methodology to combine and process these criteria. Our prior knowledge about the VCL based tactical communications systems is that, mobiles move in clusters to achieve a goal. So, the likelihood of a cluster having an access point moving together with the cluster is very high. Hence, in our algorithm, we consider relative speeds and directions of components as handoff decision metrics.

VCL based tactical communications systems use Code Division Multiple Access (CDMA) as their air interface. CDMA systems are mainly interference limited. Increasing the interference reduces directly the system capacity. So in our handoff decision algorithm, we also consider the soft capacities of access points that are affected by the interference in the environment.

We use a fuzzy logic system with center average defuzzifier, product-inference rule, and singleton fuzzifier to combine and process the handoff decision metrics. Details of the fuzzy logic systems can be found in [20]. Figure 4 shows the block diagram of our system.

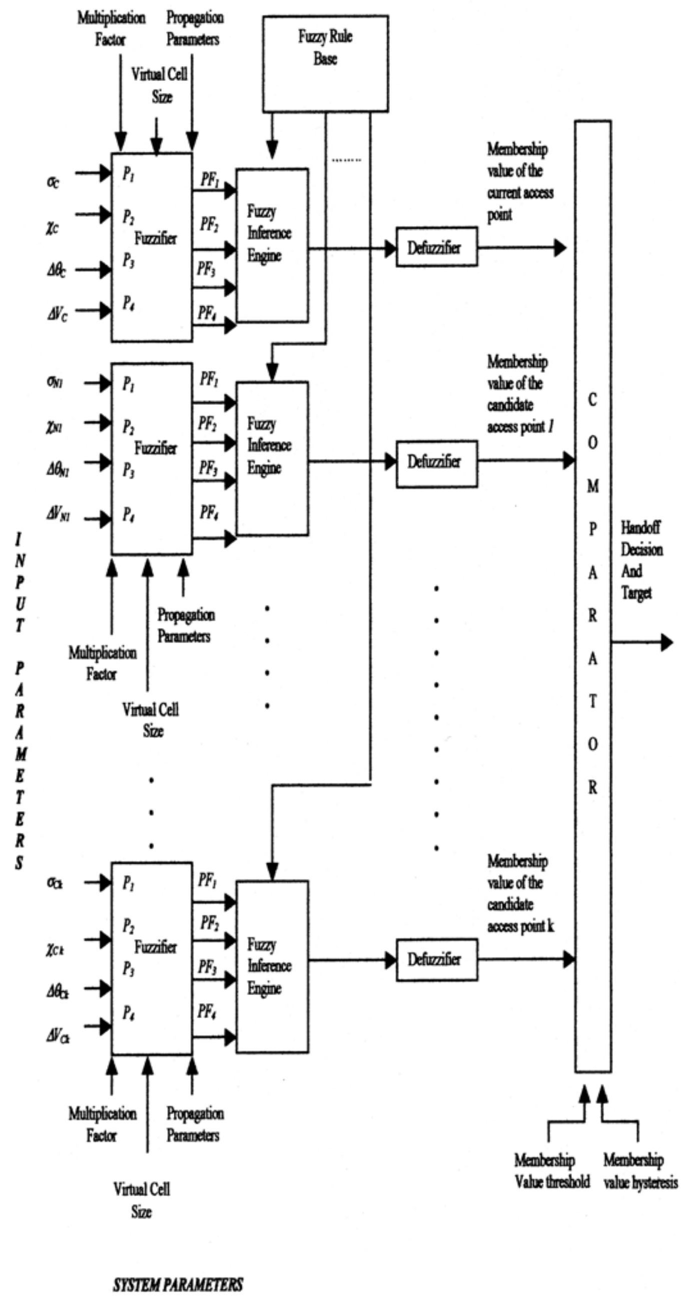

Figure 4. Block diagram of the handoff decision system.

We define a four-dimensional pattern vector for the current access point:

$$PV_C = [\sigma_c; \chi_c; \Delta\theta_c; \Delta V_c] \quad (1)$$

where, σ_c is the received signal strength from the currently serving access point, χ_c is the ratio of the used soft capacity to the total soft capacity for the currently serving access point, $\Delta\theta_C$ is the direction difference between the MPR and the currently serving access point, and ΔV_C is the velocity difference between the MPR and the currently serving access point.

We also define a four-dimensional pattern vector for the candidate access point:

$$PV_N=[\sigma_N; \chi_N; \Delta\theta_N; \Delta V_N] \tag{2}$$

where, σ_N is the received signal strength from the candidate access point, χ_N is the ratio of the used soft capacity to the total soft capacity for the candidate access point, $\Delta\theta_N$ is the direction difference between the MPR and the candidate access point, and ΔV_N is the velocity difference between the MPR and the candidate access point.

To obtain the current and the candidate received signal strengths, the mobile monitors the pilot signal of the currently serving access point and candidate access points. The total soft capacity of an access point can be found from Equation 3 [21]. Used soft capacity of an access point is the total number of used channels of that access point. Increasing interference reduces the total soft capacity of an access point.

$$N_S = \left(\left(\frac{W/R}{\overline{E}_b/N_0} - (I/S) - 1\right)\frac{1}{\alpha}\right) + 1 \tag{3}$$

where W is the total bandwidth, R is the information bandwidth, and W/R is the processing gain, E_b/N_0 is the ratio of energy per bit to noise density, α is the voice activity factor, and I/S is the ratio of interference to the desired signal. Thus χ_c, or χ_N for the respective serving and candidate access points can be found by dividing used soft capacity to the total soft capacity.

Third dimensions of the pattern vectors, namely relative direction of the mobile to the access point ($\Delta\theta$), are determined as follows; if the mobile and the access point move in the same direction, $\Delta\theta$ is zero and if they move 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 Equations 4 and 5 respectively.

$$\Delta\theta_C = |\ \theta_{MPR} - \theta_{APc}\ | \quad \text{If } (\Delta\theta_C > 180) \text{ then } (\Delta\theta_C = 360 - \Delta\theta_C) \tag{4}$$

where, θ_{MPR} is the direction of the MPR and θ_{APc} is the direction of the currently serving access point.

$$\Delta\theta_N = |\ \theta_{MPR} - \theta_{AP_N}| \quad \text{If } (\Delta\theta_N > 180) \text{ then } (\Delta\theta_N = 360 - \Delta\theta_N) \tag{5}$$

where, θ_{AP_N} is the direction of the candidate access point.

ΔV determines the relative speed of the mobile to the access point. If the speed of the mobile and the access point are the same, it is zero. ΔV_C and ΔV_N can be calculated from Equations 6 and 7 respectively.

$$\Delta V_C = |S_{APc} - S_{MPR}| \tag{6}$$

where, S_{APc} is the speed of the currently serving access point and S_{MPR} is the speed of the MPR.

$$\Delta V_N = |S_{AP_N} - S_{MPR}| \tag{7}$$

where, S_{AP_N} is the speed of the candidate access point.

Elements of the four-dimensional pattern vector are input to a fuzzifier working on the mobile. The task of the fuzzifier is to map elements of the input pattern vector to the fuzzy variables [20]. Each fuzzy variable PF_i is assigned a fuzzy value set where there is a value for each of the following fuzzy classes: LOW (L), MEDIUM (M), and HIGH (H). The fuzzifier provides us a mapping methodology from P_i to PF_i where P_i denotes the i^{th} element of the pattern vector and PF_i denotes the i^{th} element of the fuzzy pattern vector. In our algorithm, $1 \leq i \leq 4$. For example, the first element of the input pattern vector P_1, denotes σ_c or σ_N, is mapped to a fuzzy variable PF_1 by the fuzzifier.

Fuzzifier maps P_i to PF_i using membership functions in Figure 5, and creates the four-dimensional fuzzy pattern vector PV_F given below:

$$PV_F=[PF_1,PF_2,PF_3,PF_4] \tag{8}$$

Figure 5a shows the membership functions for P_1. 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 l dB and the mean received signal strength at distance $d/3$ from access point is t dB. Membership functions for the ratio of the used soft capacity to the total soft capacity, i.e., P_2, are as in Figure 5b. Relative direction of the mobile and the access point is the third element P_3 of the input pattern vector. Membership functions for P_3 are as in Figure 5c. Relative speed of the mobile and the access point is the fourth element P_4 of the input pattern vector. Membership functions for P_4 are as in Figure 5d.

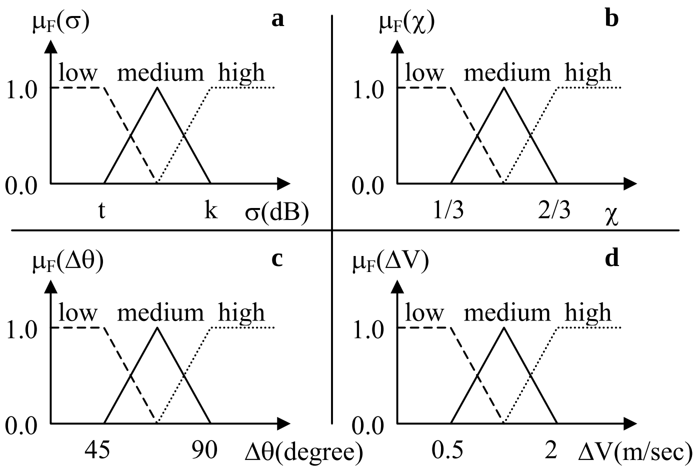

Figure 5. Membership functions of three fuzzy sets, namely, 'LOW', 'MEDIUM', and 'HIGH': (a) for the received signal strength σ (b) for the capacity utilization χ (c) for the difference in movement direction $\Delta\theta$ (d) for the difference in speed ΔV.

For example, if P_3 has the value of 56.25 degree, corresponding PF_3 is [0.5,0.5,0]. Since, $\mu_{LOW}(56.25)=0.5$, $\mu_{MEDIUM}(56.25)=0.5$, and $\mu_{HIGH}(56.25)=0$ as apparent from Figure 5c.

One of the important components of our system is the rule base. We keep 81 rules in our rule base. Since there are four fuzzy variables in the fuzzy pattern vector and three fuzzy sets for each fuzzy variable, maximum possible number of rules is $3^4 = 81$. Consequences of these implicative rules are determined by classifying these rules into one of the nine classes. This classification is performed by employing a voting mechanism between the elements of the pattern vectors. Since we have four representatives, which are the elements of the pattern vector, we may have 9 different consensus states, including draw. We call these consensus states *rule classes*. Each of these classes gives the current membership degree of a mobile to an access point. The value of one is the lowest degree of the membership and indicates a possible handoff to another access point. The value of nine is the highest degree of the membership. Figure 6 shows example rules from our fuzzy rule base.

In Rule 1, we have low received signal strength from the access point, high ratio of the used soft capacity to total soft capacity for the access point, the mobile and the access point are going nearly to the opposite directions, and there is high speed difference between the access point and the mobile. So, each element of the input pattern vector votes *bad* for this access point. So agreement for the badness of the access point is four. This is the lowest degree of membership and the rule class is 1. Similarly, In Rule 81, we have high received signal strength from the access point, low ratio of the used soft capacity to the total soft capacity for the access point, the mobile and the access point are going nearly to 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 *good* for this access point. So, agreement for the goodness of the access point is four. This is the highest degree of membership and the rule class is 9. Figure 7 shows the classes of the rules corresponding to the agreement about the access point.

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 6. Rules in the fuzzy rule base.

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		

Figure 7. Classes of the rules corresponding to the result of voting between the elements of the input pattern vector

Input of the fuzzy inference engine is the four-dimensional fuzzy pattern vector. We use the product-inference rule in our fuzzy inference engine. Hence, for a new pattern vector, contribution of each rule in the fuzzy rule base is given by Equation 9 [20].

$$C_r = \prod_{i=1}^{4} \mu_{F_i}(P_i) \tag{9}$$

where, $\mu_{F_i}(P_i)$ is the membership value of the P_i to fuzzy set F_i, and obtained from Figure 5 for P_1 through P_4.

We have 81 rules and we use a center average defuzzifier. So, the output of the defuzzifier is given by Equation 10 [20].

$$M_a = \frac{\sum_{l=1}^{81} y^l (\prod_{i=1}^{4} \mu_{F_i} (P_i))}{\sum_{l=1}^{81} (\prod_{i=1}^{4} \mu_{F_i} (P_i))} \quad (10)$$

where, y^l is the output of the rule l, which is obtained from the rule base and M_a is the membership value to the access point.

Each mobile tracks a set of access points (SoA) whose pilot signals are received. The calculations above are done for each element of the 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. If the membership value to the current access point is dropped below the membership value threshold, an access point having a membership value better than the current access point's membership value by at least an amount of the membership hysteresis value is the candidate access point for a handoff. That is;

$$\text{Handoff to the } AP_i \text{ if } (M_C < M_t) \text{ AND } (M_{Ni} - M_h > M_C) \quad (11)$$

where, M_C is the membership value to the current access point, M_t is the membership value threshold, M_h is the membership value hysteresis, and M_{Ni} is the membership value to the access point i (AP_i), $i \in [1..n]$, where n is the number of access points that the mobile is in the range of, and $AP_i \in$ SoA. The mobile has the highest membership value for AP_i among its set of candidate access points, i.e., SoA.

IV. SIMULATION RESULTS

We use Computer Aided Exercises Interacted Tactical Communications Simulation (CITACS) [22] to evaluate the performance of the proposed handoff decision algorithm. CITACS is a simulation system developed in the Network Laboratory (NETLAB) of Bogazici University. Our mobility model is based on real war game simulation data obtained from the Joint Theater Level Simulation JTLS [22]. We use two scenarios; the first has two hours duration, 4466 MPRs, and 26 RAPs. The second has thirty minutes duration, 3452 MPRs, and 20 RAPs. Simulation area is 85 km × 40 km in size. These scenarios and the CITACS are also available on the Internet [23].

Our call durations and interarrival times are exponentially distributed. Mean values of the distribution are determined according to a statistical study done in [17, 22]. In this statistical study, mean values change according to the unit type and the posture.

Since, most of the time, the battlefield is an open rural area, we use a propagation model with 2 dB path loss exponent and free space propagation up to the Fresnel breakpoint, shadowed propagation with 4 dB path loss exponent and 4 dB shadow fading standard deviation after the Fresnel breakpoint. We use 2 m transmitter and receiver antennas and 1800 MHz carrier frequency, which make the Fresnel breakpoint about 100 m away from the access point.

We also assume one carrier with 5 MHz bandwidth in each VCL cell. If connecting real time traffic like voice, teleconference, and video teleconference cannot reach its destination due to the 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 assume the E_b/N_0 value as 5 for adequate communication quality.

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

The multiplication factor determines the real coverage area of an access point. For example, for the multiplication factor 2 with 2000 m VCL cell radius, the real coverage area of an access point will be 4000 m (2 × 2000 m). We examine handoff algorithms for VCL cell radii 1000 m, 2000 m, and 4000 m. For each VCL cell radius, we examine the multiplication factors 1 and 2.

Each performance value reported 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.

In Figure 8, we observe that the RSS algorithm has better call blocking performance than the RSS with threshold algorithm and the RSS with hysteresis algorithm for the multiplication factor 1. We also observe from Figure 8 that our algorithm, namely Multicriteria-handoff Decision Algorithm (MDA), with membership value threshold 9 has the best call blocking performance. The confidence intervals do not overlap for the VCL cell radius 4000 m; hence the difference is significant. When we set the VCL cell radius to 2000 m, we observe that the confidence intervals for the MDA with membership value threshold 9 and the RSS handoff algorithm overlap. However, the mean values are outside the range of each other's confidence interval. So, we can perform a t-test to decide if MDA with membership value threshold 9 is better than the RSS based handoff algorithm for VCL cell radius 2000 m, and multiplication factor 1. The result of the t-test is that MDA with membership value threshold 9 is better than the RSS handoff decision algorithm for VCL cell radius 2000 m and the multiplication factor 1. When VCL cell radius is 1000 m, the mean value of the MDA with the membership value threshold 9 is in the range of the RSS handoff algorithm's confidence interval. Although the mean value and confidence intervals are better than the RSS algorithm for the MDA with membership value threshold 9, there is no significant difference between them for VCL cell radius 1000 m and the multiplication factor 1. MDA with membership value threshold 9 has better call blocking performance than the MDA with membership value threshold 1. The reason is: when the membership value threshold is 9, mobiles are handing off to another access point whenever an access point with higher membership value exists. In other words, the mobile's membership value to every candidate access point is below the membership value threshold. So, the mobile hands off to any access point to whom it has a membership value higher than the currently registered access point. As observed from Figure 9, the result is increased number of handoffs. When the membership value threshold is set to one, mobiles do not handoff to another access point as long as they receive acceptable service from their current access point. The result is the decreasing number of handoffs however the call blocking performance increases for higher membership value thresholds. The reason is the increased global interference. This behavior can also be observed from Figure 9. We observe from Figure 8 that even MDA with membership value threshold 1 has better mean values than RSS based algorithms, when the call blocking performance is considered.

In Figure 10, we observe that the MDA with membership value threshold 9 has better call blocking performance than the RSS handoff decision algorithm for the multiplication factor 2. As shown in Figures 9 and 11, the MDA with membership value threshold 1 achieves the minimum number of handoffs among other handoff decision algorithms, and the MDA with membership value threshold 9 has better performance than the RSS handoff decision algorithm, when the number of total handoffs is considered.

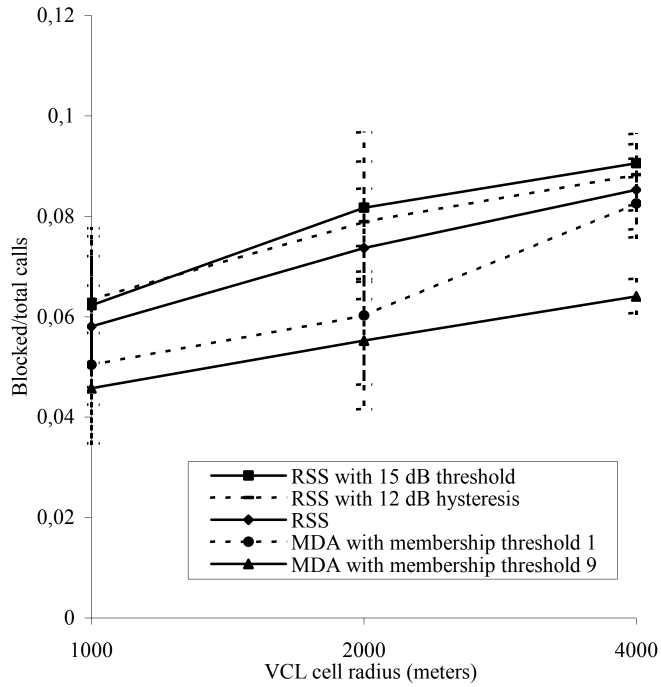

Figure 8. Comparison of handoff decision algorithms in terms of blocked calls due to lack of network resources for the multiplication factor 1.

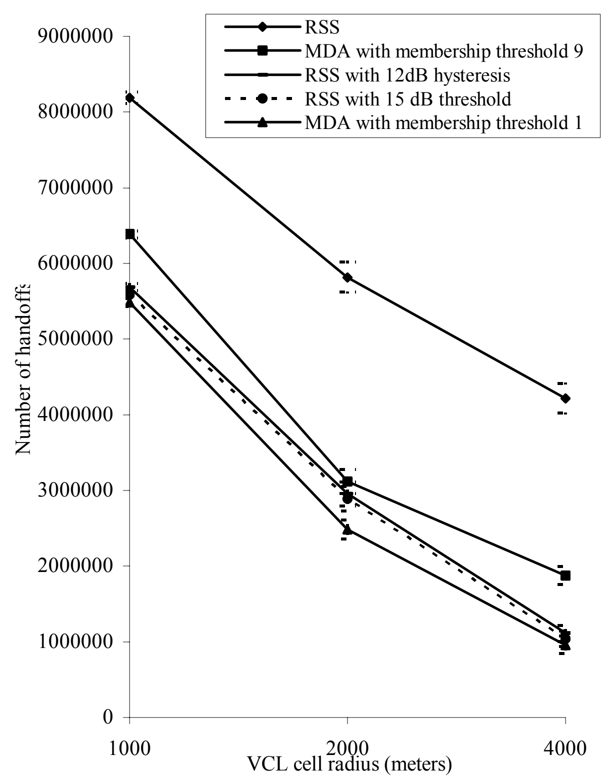

Figure 9. Comparison of handoff decision algorithms in terms of total number of MPR level handoffs for the multiplication factor 1.

We carried out another set of experiments using the scenario, which has thirty minutes duration, 3452 MPRs, and 20 RAPs. The simulation area is 85 km x 40 km in size. From Figures 12 and 13 we observe that the call blocking performance of the MDA is better than the other algorithms. Figures 14 and 15 show that MDA with membership threshold 1 has the least number of MPR level handoffs among other algorithms. These results comply with the results obtained from the first scenario. In Figures 12 and 14 the multiplication factor is 1, and in Figures 13 and 15 the multiplication factor is 2.

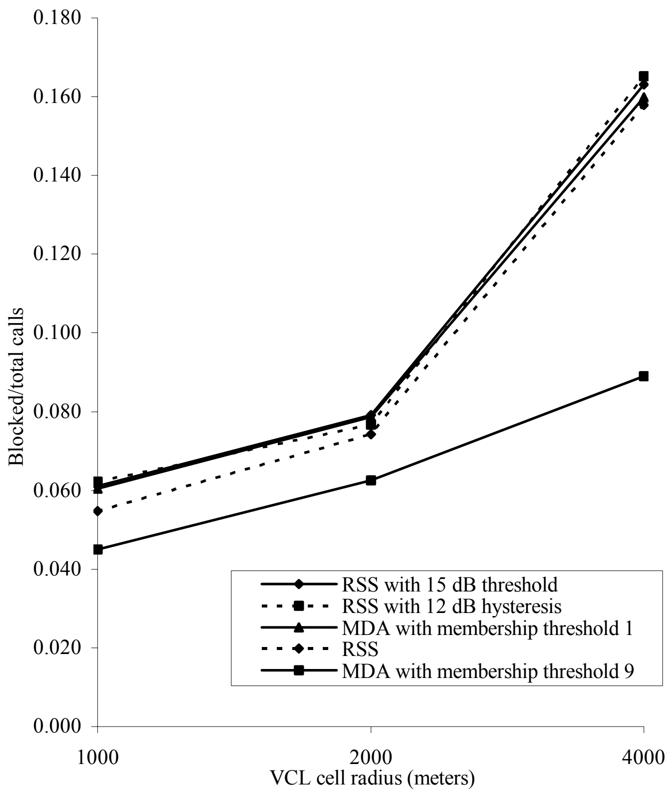

Figure 10. Comparison of handoff decision algorithms in terms of blocked calls due to lack of network resources for the multiplication factor 2.

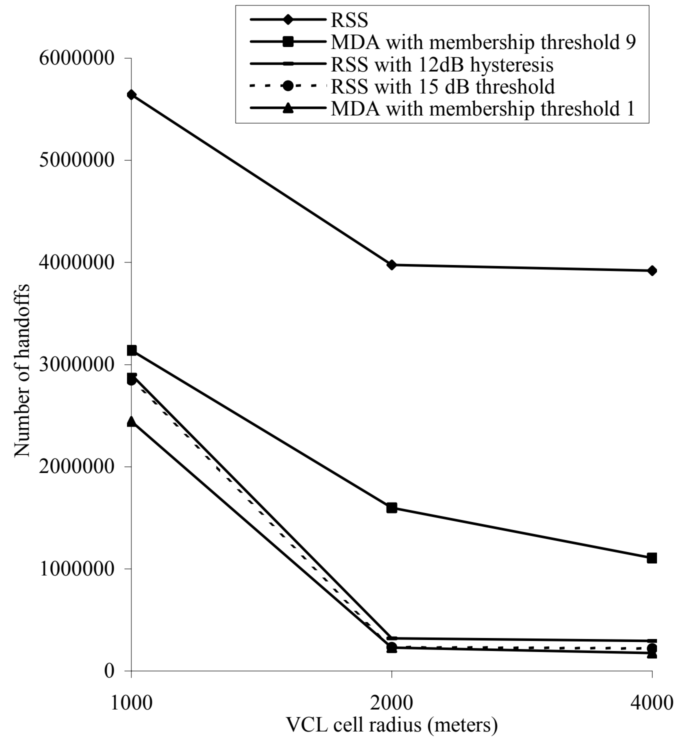

Figure 11. Comparison of handoff decision algorithms in terms of total number of MPR level handoffs for the multiplication factor 2.

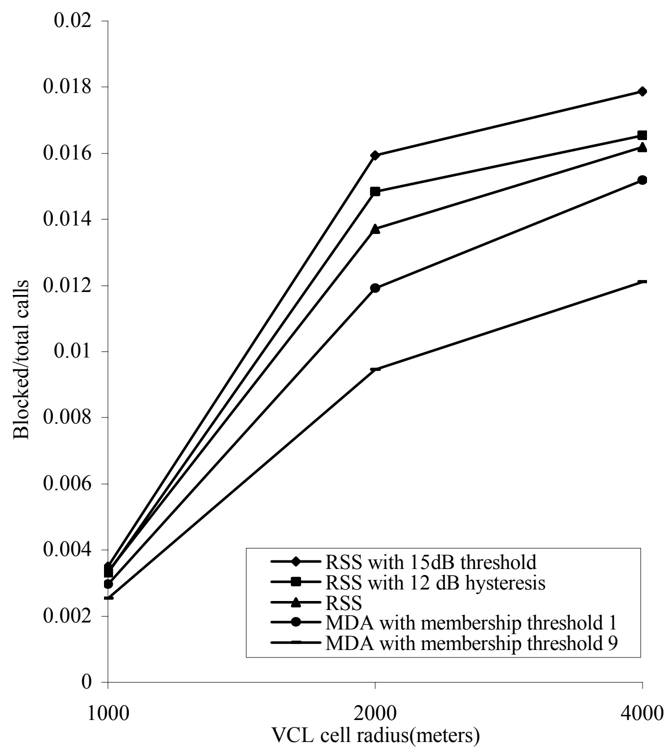

Figure 12. Comparison of handoff decision algorithms for the second scenario, in terms of blocked calls due to lack of network resources for the multiplication factor 1.

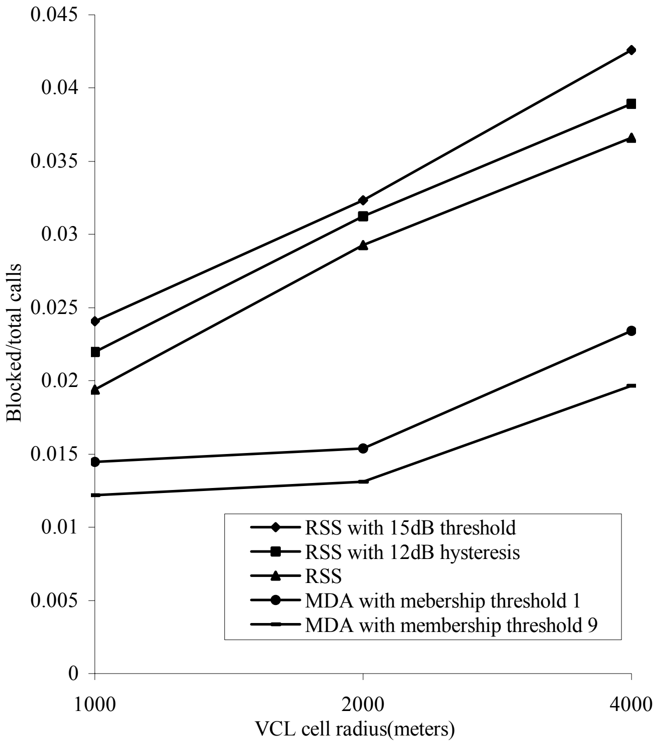

Figure 13. Comparison of handoff decision algorithms for the second scenario, in terms of blocked calls due to lack of network resources for the multiplication factor 2.

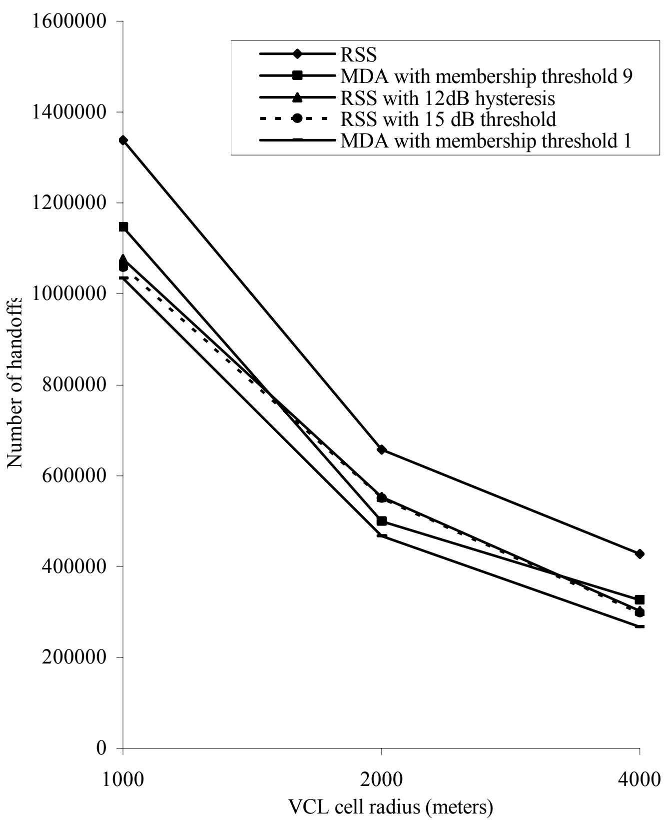

Figure 14. Comparison of handoff decision algorithms for the second scenario, in terms of total number of MPR level handoffs for the multiplication factor 1.

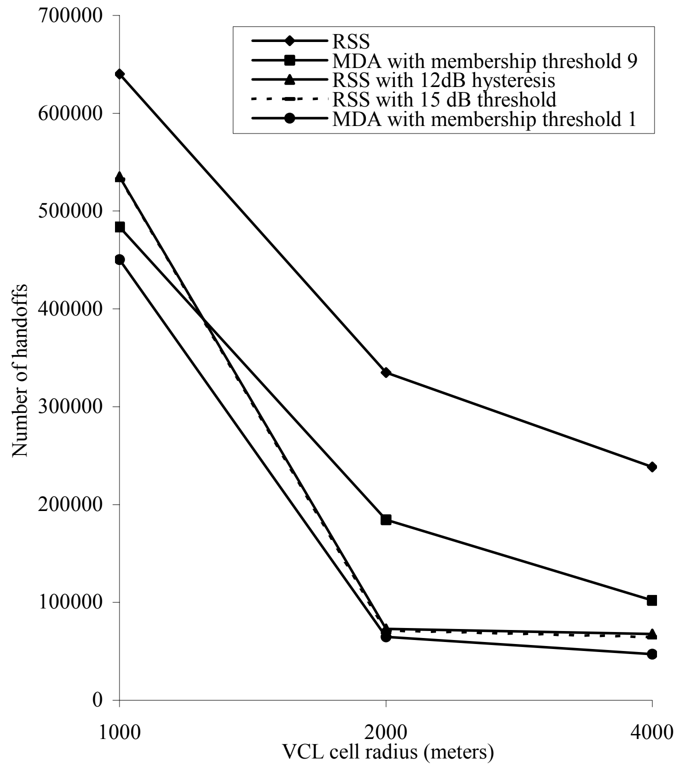

Figure 15. Comparison of handoff decision algorithms for the second scenario, in terms of total number of MPR level handoffs for the multiplication factor 2.

We also carried out simulations to examine how each component of the multicriteria handoff decision algorithm, namely received signal strength from the access point, ratio of the used soft capacity to total soft capacity for the access point, and relative direction and speed of the mobile to the access point, affects the call blocking rate and the total number of MPR level handoffs. We investigated the partial effects of these components for the case when the virtual cell radius is 2000 m and the multiplication factor is 2. We neutralize the impact of the capacity, relative speed and the relative direction one by one in our simulations.

We observe in Figure 16, that we achieve the least call-blocking rate when soft capacity and the received signal strength are used as the decision components. However, the penalty is an increased number of handoffs as shown in Figure 17. Results obtained from the first and second scenarios are compatible. We have better performance when we consider relative speed with the received signal strength compared to the case where relative direction and received signal strength are used.

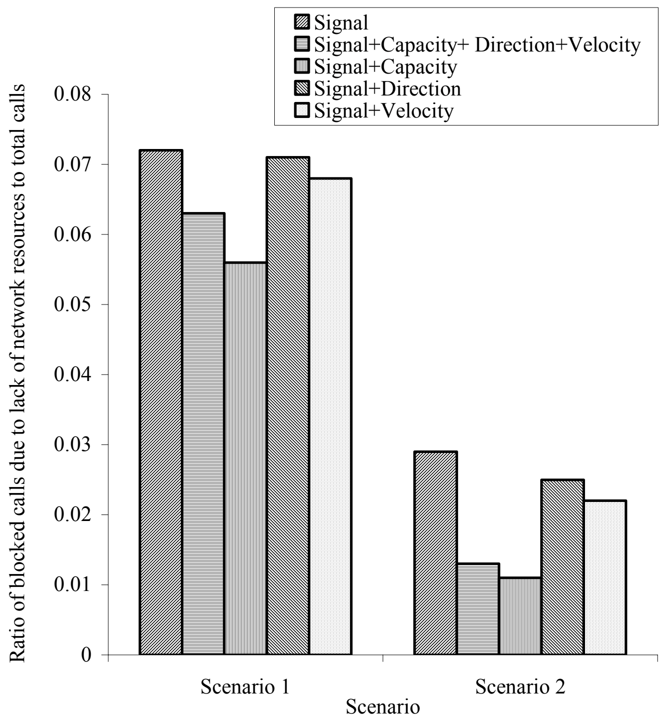

Figure 16. Partial effect of the handoff decision components on the ratio of blocked calls due to lack of network resources to total calls.

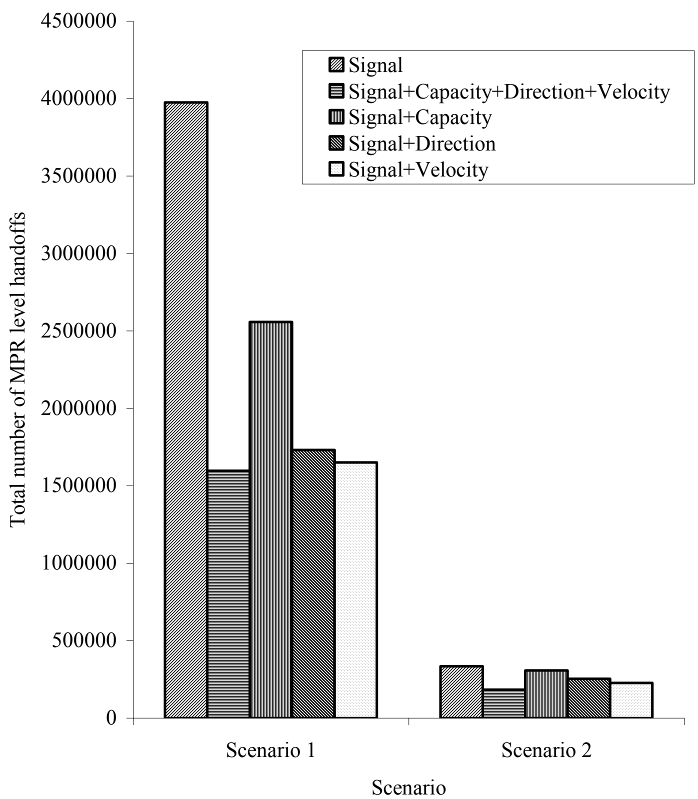

Figure 17. Partial effect of the handoff decision components on the total number of MPR level handoffs.

V. CONCLUSIONS

For mobile communications 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.

We introduced a handoff decision algorithm based on fuzzy inference systems for the networks that have a mobile infrastructure. We tested our algorithm with a tactical communications system [17], 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 the other algorithms with 95% confidence. We tested our algorithm with the membership threshold values one through nine. We observed that with the membership value threshold one, we achieved the minimum number of handoffs, and less blocked call ratio than the received signal strength based handoff decision algorithms. So we recommend one as membership value threshold for generic cases with our algorithm.

Among the handoff decision criteria used in the proposed algorithm, ratio of the used soft capacity to the total soft capacity for the access point has the largest effect on the call blocking rates. Moreover, for the studied cases, relative speed has more effect than the relative direction.

The VCL based mobile subsystem proposed in [17] is a rapidly deployable cellular architecture with a mobile infrastructure. That can be used to provide the battle forces with a tailorable, scalable and robust tactical communications system that can also convey multimedia traffic for the state of art command and control systems. The new multicriteria handoff decision scheme introduced for the VCL based mobile subsystems in this paper provides an optimization mechanism with the tradeoff between handoff and call dropping rates. It also improves the soft capacity of the system and the grade of service.

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