Signal-Based Evaluation of Handoff Algorithms

Malka N. Halgamuge, *Student Member, IEEE*, Hai Le Vu, *Member, IEEE*, Kotagiri Ramamohanarao, and Moshe Zukerman, *Senior Member, IEEE*

***Abstract*— We propose a new framework, based on signal quality, for performance evaluation and comparison between existing handoff algorithms. It includes new call quality measures and an off-line cluster-based computationally-simple heuristic algorithm to find a near optimal handoff sequence used as a benchmark. We then compare existing handoff algorithms and identify the trade-off between signal quality and number of handoffs.**

***Index Terms*— Cellular networks, wireless, handoff, handover, performance evaluation, signal quality.**

I. Introduction

INCREASED demand for mobile services has led to a reduction in cell radius and more handoffs. It is therefore of importance to provide telecommunication providers with the right criterion for evaluating handoff algorithms and choosing the one that enables them to meet customers quality of service (QoS) requirements at competitive cost.

In this paper, we promote the user signal level as a key criterion for evaluation of handoff algorithms in addition to other handoff evaluation approaches such as delay [1] and call dropping probability [2]. We also introduce an off-line heuristic algorithm which obtains a near optimal "best" handoff sequence (BHS) that can be used as a benchmark. We consider the following handoff strategies.

- The *Threshold* method [4] initiates a handoff when $(S_s < T_{HO}) \cap (S_n > S_s)$, where S_s is a signal strength of a serving base station, S_n is the highest signal strength among neighboring base stations, T_{HO} is a predefined threshold.
- The *Hysteresis* method [3] initiates a handoff when $S_n > S_s + H$, where H is a given hysteresis threshold.
- The *Threshold with Hysteresis* method [3] is a combination of above two methods. It initiates a handoff when $(S_s < T_{HO}) \cap (S_n \geq S_s + H)$. This method is often used in practice with $+3$ dB hysteresis margin.
- *Fuzzy Handoff Algorithm (FHA)* [5] uses prototypes assigned to each cell to determine the serving base station.

II. Proposed Measures for Handoff Evaluation

Consider a cellular mobile network with M base stations designated $B_1, B_2, ..., B_M$. Define $\mathcal{B} = \{B_1, B_2, ..., B_M\}$. Let a sample path l be an arbitrary path in which a mobile user is traveling. Consider a set of paths denoted Θ for the purpose of evaluating handoff algorithms. Sample points are points on the sample path for which the signal strength received from base stations are measured. Let S_{ij} be the signal strength at sample point i received from base station B_j. Define a handoff sequence x or $x(l)$ of sample path l, as a sequence of base stations assigned to the sample points in l, assigning $b_i \in \mathcal{B}$ to the i^{th} sample point, i.e., $x =< b_1, b_2, ..., b_N >$ where N is the number of sample points. (Note that b_i and b_j, $\forall i, j$ may designate the same base station.)

For every sample path, define the set of all possible handoff sequences as $X = \{x_i | 0 < i \leq M^N\}$. The number of handoffs $\gamma(x)$ in a handoff sequence x equals to the number of changes in the base station sequence. For example, the handoff sequence $x = \{B_1, B_1, B_2, B_3, B_3, B_3\}$ has $\gamma(x) = 2$.

For a given handoff sequence $x \in X$, define, $S_i(x) = S_{ij}$ such that $B_j = b_i$, $b_i \in x$. Let S_{min} be the minimum signal strength below which the signal quality is unacceptable to the user. Let $S_{max} > S_{min}$ be the signal strength beyond which the marginal benefit is considered negligible. For a given sample path and its associated handoff sequence, we define the following signal quality measures.

1) Average Received Signal Strength ($ARSS(x)$) is defined by $\frac{1}{N}\sum_{i=1}^{N} S_i(x)$.
2) Number of Acceptable Sample Points ($NASP(x)$) represents the number of sample points of the handoff sequence with signal strength above S_{min}. Let $\Omega_x = \{i | S_i(x) \geq S_{min}\}$, then $NASP(x) = |\Omega_x|$, where $|\Upsilon|$ denotes the number of elements (cardinality) in the set Υ.
3) The concept of Call Quality Signal Level ($CQSL(x)$) proposed in this paper combines the above two measures and is defined by

$$CQSL(x) = \frac{\sum_{i \in \Omega_x} A_i(x)}{|\Omega_x|} - CN(x), \qquad (1)$$

where $A_i(x) = S_i(x)$ if $S_i(x) < S_{max}$, otherwise $A_i(x) = S_{max}$, and $N(x) = (N - |\Omega_x|)$ is the number of samples with signal strength lower than S_{min}, and C is the cost (or the penalty) for an unacceptable sample point. We assign $\sum_{i \in \Omega_x} A_i(x)/|\Omega_x|$ to zero when $|\Omega_x| = 0$.

Let p be the maximum allowed proportion of sample points with signal quality below S_{min}, i.e., $N(x)/N \leq p$. The p value may be agreed between the service provider and the user. Assuming $|\Omega_x \neq 0|$, the minimum value that $CQSL(x)$ can take is when (i) $N(x)/N = p$ and (ii) $\sum_{i \in \Omega_x} A_i(x)/|\Omega_x| = S_{min}$ in (1). We choose C such that the above minimum value

Manuscript received February 3, 2005. The associate editor coordinating the review of this letter and approving it for publication was Prof. Carla-Fabiana Chiasserini. This work was supported by the Australian Research Council (ARC).

The authors are with the ARC Special Research Center for Ultra-Broadband Information Networks, an affiliated program of National ICT Australia, Department of Electrical and Electronic Engineering, The University of Melbourne, Melbourne, VIC 3010, Australia (e-mail-m.zukerman@ee.mu.oz.au).

Digital Object Identifier 10.1109/LCOMM.2005.09011.

is greater than or equal to zero. The parameter C in (1) can be bounded as follows:

$$C \leq \frac{\sum_{i\in\Omega_x} A_i(x)/|\Omega_x|}{N(x)} = \frac{S_{min}}{pN}. \quad (2)$$

Here we choose the cost to be linear. However, we could also set it up dynamically to reflect the fact that consecutive unacceptable sample points are worse than a single unacceptable sample point. Using (1) and (2), we obtain

$$CQSL(x) \geq \frac{\sum_{i\in\Omega_x} A_i(x)}{|\Omega_x|} - \frac{S_{min}(N-|\Omega_x|)}{pN}. \quad (3)$$

The measures $ARSS(x)$, $NASP(x)$, and $CQSL(x)$ are defined for any $x \in X$ on an arbitrary sample path $l \in \Theta$. For a given handoff algorithm there is at least one optimal handoff sequence for a given l according to the algorithms criteria. Assuming that all sample paths are independent, and equally important, different handoff algorithms will be evaluated by averaging the values of these measures over all the sample paths. For example we use the average: $\overline{CQSL} = \sum_l [CQSL(x(l))]/\eta$, where $\eta = |\Theta|$.

In (3) the parameter p is related to call dropping probability. In practice, a call is dropped if either the high co-channel interference, or the signal level below a certain threshold $S_{drop} < S_{min}$ (call dropping condition) is maintained for d consecutive samples in the handoff sequence. (We use this simple criteria to model duration of bad connections.)

Let P_{drop} be the probability that a call is dropped. For a sample path l, let δ_l be the probability of receiving a signal strength below S_{drop}. Let μ_l be the probability of receiving co-channel interference above a specified value. Therefore, the call dropping probability in the sample path l with $N_l > d$ consecutive sample points is given by the following recursive formulae:

$$P_{drop_l}(N_l) = P_{drop_l}(N_l - 1) + P_l^d(1-P_l)(1-P_{drop_l}(N_l-d-1)), \quad (4)$$

where the probability of having a single sample point satisfying the call dropping condition is $P_l = 1-(1-\delta_l)(1-\mu_l)$, $P_{drop_l}(N_l < d) = 0$ and $P_{drop_l}(N_l = d) = P_l^d$. If the co-channel interference is neglected then $P_l = \delta_l$. The average call dropping probability over η sample paths is:

$$P_{drop}(N_l, d) = \frac{1}{\eta}\sum_{l=1}^{\eta} P_{drop_l}(N_l). \quad (5)$$

Given a number of sample points N_l, the value of d can be determined such that $P_{drop}(N_l, d)$ in (5) is below a certain threshold according to a QoS requirement. The value of p in (3) is chosen to be $\geq d/N_l$. Knowing p, for a given handoff sequence of a sample path with $N_l = N$ sample points, we can calculate the minimum value of $CQSL(x)$ using (3).

Furthermore we introduce the signal quality per handoff:

$$\lambda = \overline{CQSL}/\overline{\gamma}, \quad (6)$$

where $\overline{\gamma} = \sum_l [\gamma(x(l))]/\eta$. We will use (6) to compare different handoff methods in section IV.

III. The Best Handoff Sequence (BHS)

Our aim here is to obtain the BHS defined by the following multiple objective unconstrained optimization problem:

$$\max_{x\in X} \ (1-a)\psi(x) - a\gamma(x), \quad (7)$$

where $\psi(x) = \sum_{i\in\Omega_x} A_i(x)/|\Omega_x| - S_{min}(N-|\Omega_x|)/pN$, and $a \in [0,1]$, the weight factor indicates the relative importance of the two objectives $\psi(x)$ and $\gamma(x)$. Since all the paths are independent, maximisation of $CQSL(x(l))$ for any path l also maximizes $\overline{CQSL}$. Note that in [1] only two base stations are considered and therefore an exhaustive search for the optimal handoff sequence is used. In our case exhaustive search is impractical because of a large number of possible sample paths (M^N) involved. Therefore, we propose a heuristic method based on the so-called cluster approach.

Let G_{ij}, referred to as a cluster, be a set of signal strengths $\geq S_{min}$ from base station j associated with a group of consecutive sample points $\{i, i+1, ..., i+L_{ij}-1\}$, where $1 \leq L_{ij} = |G_{ij}| \leq N-i+1$. Let $W_{ij} = \sum_{r=i}^{i+L_{ij}-1} S_{rj}/L_{ij}$.

In order to solve (7) our heuristic algorithm maximises $\psi(x)$ by finding maximum average signal level W_{ij} and at the same time minimises the number of handoffs $\gamma(x)$ by choosing longest clusters ($\max L_{ij}$).

Let H_{ij} be the parameter associated with a cluster G_{ij} which is defined as the weighted value

$$H_{ij} = \alpha L_{ij} + (1-\alpha)W_{ij}, \quad (8)$$

where $\alpha \in [0,1]$. According to (8) when $\alpha = 0$, $H_{ij} = W_{ij}$, and hence maximises signal quality, and when $\alpha = 1$, $H_{ij} = L_{ij}$, and hence maximises the cluster length.

Let Φ be a signal strength matrix of $N \times M$, received from M base stations with N sample points for a particular sample path. Here, we aim to find the BHS as a set of G_{ij} starting from the first row ($i = 1$) until the last row ($i = N$) in Φ, which maximizes the optimization function (7). Our heuristic algorithm is described as follows.

Step 0: Set $i = 1$.

Step 1: At the i^{th} sample point in Φ the algorithm finds all clusters which start from this i^{th} sample point, it then selects the cluster G_{ij^*} with maximum value of H_{ij}, i.e., $G_{ij^*} = \arg\max_{G_{ij}} H_{ij}$. If there is only a single cluster starts from the i^{th} sample point, then automatically it will be selected. If there is no cluster starting from i then go to **Step 2**. The algorithm assigns the base station j^* associated with the selected cluster as the serving base station for the $\{i, i+1, .., i+L_{ij^*}-1\}$ sample points. If $i + L_{ij^*} < N$ then return to **Step 1** with $i = i + L_{ij^*}$ until $i = N$.

Step 2: Starting from row i the algorithm skips all the rows in Φ until it finds a new row u with a cluster G_{uv} containing at least one sample point with signal strength $> S_{min}$ (i.e. $L_{uv} \geq 1$). Return to **Step 1** with this u^{th} sample point to find the G_{uv^*} cluster with maximum value of H_{uv}. In addition, for the above skipped sample points between $\{i, .., u-1\}$, the algorithm assigns the previous serving base station j^* (no handoff) or the new serving base station v^* (handoff) such that the average signal strength over all the skipped sample points is maximized. If no such u^{th} sample point is found, then we assign the previous serving base station j^* as the new serving

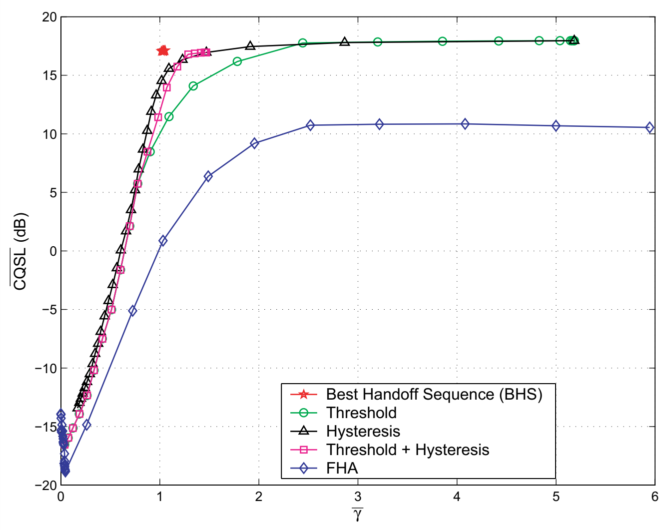

Fig. 1. Comparison of the various handoff algorithms

base station. If $u + L_{uv^*} < N$ then return to **Step 1** with $i = u + L_{uv^*}$ until $i = N$.

IV. Simulation Results

Here we compare the different handoff methods introduced in Section I using the quality measures of (3) and (6). We consider $M = 3$ adjacent cells with 100 m radius. The base stations are located in a plane with the following coordinates: $(100, 150)$, $(250, 75)$ and $(250, 250)$ [meters]. We randomly generate $\eta = 1000$ sample paths, each with $N = 100$ where each pair of consecutive points are one meter apart. A log-normal propagation model [6] was assumed to generate signal strengths in each sample point along all the sample paths, i.e., $S_{ij} = K_1 - K_2 log(r) + F$, where $K_1 = 85$; $K_2 = 35$ are constants, r is the distance to the base station, and F is Gaussian distributed $(N(0, \sigma^2))$ representing the shadowing effect. We set $\sigma = 3$ dB as in [1], shadowing correlation distance equals 20 m, $S_{min} = 15$ dB as in [5] and $S_{max} = 1.5 S_{min}$. All the sample paths are straight lines that start from points in the square area $\{(100, 100), (200, 100), (200, 200), (100, 200)\}$. Their directions are randomly chosen between $[0, 2\pi]$ uniformly. Note that P_{drop} is computed by (5) as a decreasing function of d, where $d \geq 3$ gives the call dropping $\leq 1\%$. The p value in (3) is selected such that $p \geq d/N = 0.03$. Here we use $p = 0.1$.

The values of $\overline{CQSL}$ and $\overline{\gamma}$ in Fig. 1 are obtained by varying the T_{HO} threshold in the Threshold method and Threshold + Hysteresis method (with +3 dB hysteresis margin), and the H hysteresis threshold in the Hysteresis method, respectively, from 1 to 30 dB. A similar range was used when varying the so-called similarity threshold in the FHA method.

As a benchmark value, we show in Fig. 1 the $\overline{CQSL}$ and $\overline{\gamma}$ of the BHS for different values of $\alpha \in [0, 1]$ in (8). Observe that these values are almost unchanged (insensititive) for different α values which indicates that we can use either L_{ij} or W_{ij} for the cluster selection.

The complexity of the proposed heuristic algorithm is $O(MN)$ in comparison to the complexity $O(M^N)$ using exhaustive search. Using the same network but with $N = 20$ sample points, the difference between a solution resulted from an exhaustive search and ours was never more than 0.24%.

Fig. 1 shows that the Hysteresis method and Threshold + Hysteresis method (with +3 dB hysteresis margin) provide the best values that are closest to BHS. When high numbers of handoffs can be tolerated Threshold method will be as efficient as the above two. Our simulations indicate FHA is less desirable in comparison to other methods.

Based on Fig. 1, optimum parameter settings for each handoff method can be obtained from the “knee” point of the corresponding curves (similar to [1]). For example the “knee” point for the Threshold handoff method is a point with $\overline{CQSL} = 14.09$ dB and $\overline{\gamma} = 1.33$ values according to Fig. 1. This is when the threshold T_{HO} is set to 14 dB which produces highest $\overline{CQSL}$ with lowest average number of handoffs.

TABLE I

”knee” Parameter values for all handoff algorithms

Method	T_k (dB)	$\overline{CQSL}$ (dB)	$\langle \lambda , \overline{\gamma} \rangle$	$\overline{NASP}/\overline{\gamma}$
BHS	15	17.05	⟨16.88 , 1.01⟩	93.90
Thres+Hys	15	15.73	⟨13.44 , 1.17⟩	78.11
Hysteresis	6	15.56	⟨14.27 , 1.09⟩	83.73
Threshold	14	14.09	⟨10.59 , 1.33⟩	68.25
FHA	25	9.18	⟨4.70 , 1.95⟩	42.15

In Table I we compare all handoff methods at their “knee” points using the following quantities: $\overline{CQSL}$ in (3), λ in (6) and $\overline{NASP}/\overline{\gamma}$, where $\overline{NASP} = \sum_l [NASP(x(l))]/\eta$. The optimal threshold for each method at the “knee” point is presented in column identified with T_k in dB. The benchmark BHS has the highest λ and $\overline{NASP}/\overline{\gamma}$ values. We repeated our experiment for various N values ($N = 50, 100, 200$) and found the results to be consistent.

V. Conclusion

A signal level based criterion is developed for the evaluation of handoff algorithms. We have proposed new call quality measures and developed an off-line cluster-based computationally-simple heuristic algorithm to find a near optimal handoff sequence that can be used as a benchmark. Our results show that there is substantial room for improvement in existing handoff algorithms with respect to the signal level measures as well as number of required handoffs.

References

[1] K. D. Wong and D. C. Cox, “A pattern recognition system for handoff algorithms,” *IEEE J. Select. Areas Commun.*, vol. 18, pp.1301–1312, July 2000.

[2] P. L. Hiew and M. Zukerman, “Efficiency comparison of several channel allocation schemes for digital mobile communication networks,” *IEEE Trans. Vehic. Technol.*, vol. 49, pp. 724–733, May 2000.

[3] S. Moghaddam, V. Tabataba, and A. Falahati, “New handoff initiation algorithm (optimum combination of hysteresis and threshold based methods),” in *Proc. IEEE Vehic. Technol. Conf.*, Sept. 2000, pp. 1567–1574.

[4] ETSI, *GSM Technical Specification*, GSM 08.08, version 5.12.0 ed., France, June 2000.

[5] H. Maturino-Lozoya, D. Munoz-Rodriguez, F. Jaimes-Romero, and H. Tawfik, “Handoff algorithms based on fuzzy classifiers,” *IEEE Trans. Vehic. Technol.*, vol. 49, pp. 2286–2294, Nov. 2000.

[6] M. Gudmundson, “Correlation model for shadow fading in mobile radio systems,” *Electronics Lett.*, vol. 27, pp. 2145–2146, Nov. 1991.