

Performance Analysis of Active Handoff in CDMA2000 Femtocells

Gauri Joshi

Department of Electrical Engineering
Indian Institute of Technology Bombay
Powai, India 400076.
Email: gauri@ee.iitb.ac.in

Mehmet Yavuz, Chirag Patel

Corporate R&D
Qualcomm Inc.
San Diego, CA 92121, USA.
Email: {myavuz,cpatel}@qualcomm.com

Abstract—Cellular operators are developing femtocells to improve network coverage for indoor users. But in current CDMA systems, heavy reuse of PN codes among femtocells causes ambiguity in choosing the target for handoff. To resolve the ambiguity, a method which uses reverse link (RL) sensing at femtocells has been proposed. This method uses RL measurements of the mobile's signal to choose the femtocell with the best forward link channel, as the handoff target. The robustness of this method to fast fading and shadowing is demonstrated in this work. By making multiple RL measurements, the error in handoff due to fading can be reduced, but at the cost of increased delay. The tradeoff between probability of error in handoff and RL measurement duration is demonstrated. It is also shown that unsynchronized measurements by femtocells cause a only marginal increase in the probability of handoff error.

Index Terms—Femtocells, Handoff, CDMA

I. INTRODUCTION

Providing good cellular coverage is challenging in dense urban neighborhoods, due to high penetration losses, and high interference levels. Femtocells solve this problem by placing a base station in close proximity to indoor users. A femtocell is a personal miniature low power base station with approximately 5-20 dBm maximum power [1]. It uses the digital subscriber line (DSL) or cable broadband connection in the user's residence as a backhaul to connect to a cellular operator's network. Benefits of femtocells include improvement in indoor network coverage and offloading of traffic from the macrocell, i.e. the serving base station. An overview of femtocells and their position in the telecommunications market today can be found in the literature [1]–[3].

Cellular operators are widely developing and deploying femtocells in third generation (3G) cellular networks. The femtocells have to be compatible with existing CDMA mobile phones. Also, femtocell deployment architecture needs to support user mobility in terms of seamless handoffs between macrocells and femtocells. In contrast to traditional macrocell-only networks, femtocell-macrocell networks pose the following new challenges to handoffs (HOs):

- Soft HOs are not possible in femtocell-macrocell networks because there is no common base station controller between the macro base station and the femtocell, which can communicate with both the base stations simultaneously, and smoothly handoff an active call. Thus a mobile

user in an active call has to make a hard HO to and from a femtocell.

- Handoff methods have to be backward compatible with legacy mobiles and the existing network architecture. During handoff, mobiles convey only the PN code of the target femtocell to the serving base station. Since only about five PN codes are reused among the femtocells, the PN code is not a unique identifier of the femtocell. This causes ambiguity in determining the handoff target.

The ambiguity in performing an active HO (i.e. when the mobile is in an active call) is solved by the reverse link (RL) sensing method, which is compatible with legacy mobiles. The method uses received mobile signal power measured by the femtocells to choose the handoff target. The femtocell with the best forward link (FL) signal to noise ratio (SNR) is chosen as the target. The RL sensing method described next has been standardized in the CDMA2000 1xRadio Transmission Technology (1xRTT) specification. The method consists of the following steps: (i) Received mobile signal power (referred to as RL measurement) is measured by femtocells, (ii) the femtocells send these measurements to the backhaul network, and (iii) the femtocell with the maximum RL measured power is chosen as handoff target (see Section II for more details).

To improve the performance of the RL sensing method, multiple RL measurements can be used at the cost of handoff delay. Backhaul network delay or unavailability of the femtocell to perform RL measurements may cause these RL measurement intervals to be unsynchronized, and increase the probability of handoff error.

Contributions: This paper analyzes the performance of the RL sensing method in terms of the probability of error in choosing the correct femtocell as handoff target. The tradeoff between probability of error in handoff and the RL measurement duration is demonstrated. The effect of unsynchronized RL measurement intervals on the probability of handoff error is studied to show that unsynchronized RL measurements cause a only marginal increase in error in handoff.

Organization: Section II gives an overview of the RL sensing method for active HO. In Section III we set up the system model used to evaluate the performance of the RL sensing method. In Section IV, the expressions for the

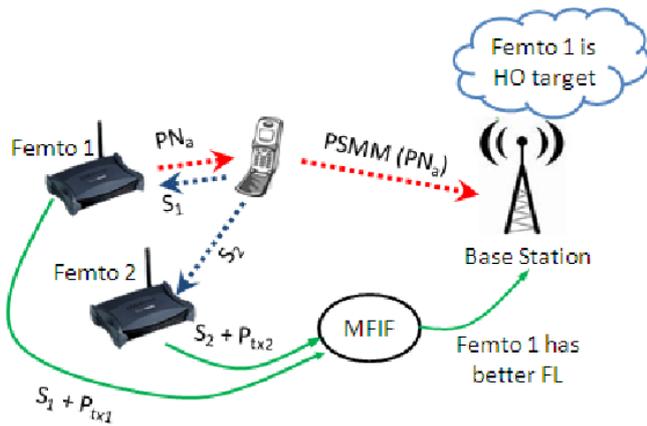


Fig. 1. The RL sensing method for active handoff in femtocells is illustrated here. Dotted lines represent wireless links and solid lines are wired links. The mobile detects a strong signal of Femto 1 and sends a PSMM with the PN_a to the base station. On request from the base station, the femtocells using PN_a sense the RL signal power from the mobile, S_1 and S_2 . The MFIF compares the quantities $(P_{Tx_i} + S_i)$ from the femtocells and chooses the maximum as the handoff target.

probability of error in choosing the correct femtocell are derived. Section V provides the analytical and simulation results of the expressions derived in Section IV. Lastly, Section VI presents the summary of the paper and specific suggestions to cellular operators to optimize the handoff to femtocells.

II. ACTIVE HANDOFF USING RL SENSING

Active HOs can be divided into two categories: (i) a HO from a femtocell to a macrocell and (ii) a HO from macrocell to a femtocell. A femtocell to macrocell active HO is quite straightforward. On detecting a strong macro base station pilot signal, the mobile reports the FL signal quality and the PN code of this signal to its serving femtocell via a Pilot Strength Measurement Message (PSMM). Since macrocells are uniquely identified by their PN code, the femtocell knows the target macrocell and triggers a HO to it.

On the contrary, a macrocell to femtocell HO has the following problem. In most practical CDMA cellular systems very few (~ 5) PN codes are reused amongst all the femtocells. The femtocell PN code conveyed by the mobile in the PSMM does not uniquely identify the target femtocell. Because of this ambiguity, the macro base station is unable to perform active HO to the correct femtocell. The RL sensing method solves this problem. Fig. 1 illustrates this method. Details of the procedure are described next.

Consider two femtocells, femto 1 and femto 2 using the same pilot PN code (PN_a). Our aim is to estimate the femtocell with the best FL (SNR), by comparing the RL mobile signal power sensed by the femtocells. Thus the FL $SNRs$ (dB) of the two femtocells at the mobile are given by

$$SNR_{FL_k} = P_{Tx_k} - PL_{FL_k} - N, \quad \text{for } k = 1, 2 \quad (1)$$

where PL_{FL_1} and PL_{FL_2} are the pathloss values to the mobile and P_{Tx_1} and P_{Tx_2} are the transmit powers (dB) of femto 1

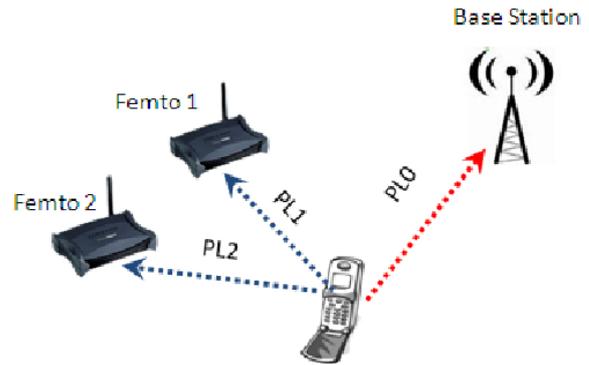


Fig. 2. The wireless network topology consists of a mobile, a macro base station and two femtocells. The pathloss values are PL_0 , PL_1 and PL_2 for the wireless links shown in the figure.

and femto 2 respectively. P_{Tx_i} is the power of the signal transmitted by a femtocell after the mobile has been handed over to it. Let us consider the difference between the two FL $SNRs$ in (2) below. Since we want to estimate the FL strength of the femtocells by using the RL measured powers, we assume that the FL and RL pathlosses are approximately equal. Also, the difference between the RL pathlosses, $(PL_{RL_2} - PL_{RL_1})$ is assumed to be equal to the difference $(S_1 - S_2)$ between the values RL mobile power measured at the femto 1 and femto 2 respectively.

$$\begin{aligned} SNR_{FL_1} - SNR_{FL_2} &= (P_{Tx_1} - P_{Tx_2}) + (PL_{FL_2} - PL_{FL_1}), \\ &\approx (P_{Tx_1} - P_{Tx_2}) + (PL_{RL_2} - PL_{RL_1}), \\ &\approx (P_{Tx_1} - P_{Tx_2}) + (S_1 - S_2), \\ &= (P_{Tx_1} + S_1) - (P_{Tx_2} + S_2). \end{aligned} \quad (2)$$

Thus, we can infer that if every femtocell using PN_a conveys the quantity $(P_{Tx_i} + S_i)$ to the macro base station, the femtocell with the maximum $(P_{Tx_i} + S_i)$ should be chosen as the handoff target. In actual implementation, the femtocells will send this measurement to an entity called the Macro-Femto-Intermediate Function (MFIF). The MFIF finds the femtocell with the maximum $(P_{Tx_i} + S_i)$ and conveys this information to the macro base station.

III. SYSTEM MODEL

A. Wireless network topology

The system topology used in our analysis is shown in Fig. 2. The mobile is currently served by the macro base station and it has to perform an active handoff to either femto 1 or femto 2 (both using the same PN code). PL_0 , PL_1 and PL_2 are pathloss values from the mobile to macro base station, femto 1 and femto 2 respectively. For simplicity, we have assumed only two femtocells in the analysis. The results can be easily extended to a larger number of femtocells.

B. Fading and shadowing model

The channel experiences log-normal shadowing and single path Rayleigh fading, the latter being modeled according to

Jakes' model in [4]. Let $F(n)$ (in dB) be the sum of the log-normal shadowing and Rayleigh fading at sample index n .

$$F(n) = Y(n) + 10 \log_{10}(X(n)^2) \quad (3)$$

where $Y(n)$ is a normal random variable for shadowing in dB and $10 \log_{10}(X(n)^2)$ is the Rayleigh fading in dB. It has been shown in [5] that $F(n)$ can be approximated as a Gaussian random variable with mean, auto-covariance as given in (4).

$$E(F(n)) = -2.5 \text{dB}, \quad (4)$$

$$\Phi_{FF}(l) = \sigma^2 e^{-\frac{vT_s l \ln 2}{d_{corr}}} + (5.57)^2 J_0(2\pi f_d T_s l)^2, \quad (5)$$

$$\text{Var}(F(n)) = \Phi_{FF}(0) = \sigma^2 + (5.57)^2. \quad (6)$$

The exponential term in (5) represents the auto-covariance of shadowing, as given in [6]; where v is the speed of the mobile, d_{corr} is the shadow correlation distance (10 to 20m), T_s is the sample interval and l is the sample index. The zeroth order Bessel function term represents autocorrelation of Rayleigh fading [4], where f_d is the maximum Doppler frequency. The shadowing standard deviation σ takes the values σ_f for the mobile-femtocell link and σ_m for mobile-macro base station link. The quantity $F(n)$ for links between the mobile and the macro base station, femto 1 and femto 2 is denoted as $F_0(n)$, $F_1(n)$ and $F_2(n)$.

C. Power control at mobiles and femtocells

The mobile controls its uplink power to maintain a constant received signal power c dB at the macro base station. Thus $c = P_T(n) - PL_0 + F_0(n)$ where $P_T(n)$ is the mobile's transmit power. For the femtocell transmit power, we assume that the two femtocells transmit equal power ($P_{Tx_1} = P_{Tx_2}$). Hence, the comparison of $(P_{Tx_1} + S_1)$ and $(P_{Tx_2} + S_2)$ in (2) for determining the handoff target reduces to choosing the femtocell with greater RL sensed power S_i .

IV. PERFORMANCE ANALYSIS OF RL SENSING

The RL signal powers sensed at sample index n , by femto 1 and femto 2 respectively are given by,

$$\begin{aligned} S_k(n) &= P_T(n) - PL_k + F_k(n), \quad \text{for } k = 1, 2. \\ &= c + PL_0 - F_0(n) - PL_k + F_k(n) \end{aligned}$$

$S_1(n)$ and $S_2(n)$ are compared to choose the handoff target. A handoff error is the event when the femtocell closest to the mobile is not chosen. An analytical expression of the probability of error in handoff (referred to as the probability of error in this paper) is derived. The expressions are evaluated for three different cases as follows:

A. Probability of error with one RL measurement

Suppose femto 1 and femto 2 each make only one instantaneous measurement of the RL mobile signals $S_1(n)$ and $S_2(n)$ respectively. They convey this value to the macro base station which selects the femtocell with the greater $S_i(n)$ as the handoff target. Without loss of generality we assume that $PL_1 < PL_2$ and hence femto 1 is the correct target for handoff. Let the difference between PL values be

$\Delta = PL_2 - PL_1$. Now, the probability of error in handoff, i.e. the probability of error in choosing the correct femtocell (assumed to be femto 1 here) as a function of Δ is

$$\begin{aligned} P_\varepsilon(\Delta) &= P(S_1(n) - S_2(n) < 0), \\ &= P(\Delta + F_1(n) - F_2(n) < 0), \\ &= P(F_2(n) - F_1(n) > \Delta), \end{aligned} \quad (7)$$

where F_1 and F_2 are independent Gaussian random variables with statistical properties as given in (4), (5) and (6). Thus $F_2(n) - F_1(n)$ also has a Gaussian distribution. Let us define it as a Gaussian random variable $H(n) = F_2(n) - F_1(n)$. Its statistical properties are

$$E(H(n)) = 0 \text{dB}, \quad (8)$$

$$\Phi_{HH}(l) = 2\sigma_f^2 e^{-\frac{vT_s l \ln 2}{d_{corr}}} + 2(5.57)^2 J_0(2\pi f_d T_s l)^2, \quad (9)$$

$$\sigma_H^2 = \Phi_{HH}(0) = 2\sigma_f^2 + 2(5.57)^2. \quad (10)$$

Thus, the probability of error in (7) becomes

$$P_\varepsilon(\Delta) = Q\left(\frac{\Delta}{\sigma_H}\right), \quad (11)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{x^2}{2}} dx$.

B. Probability of error with multiple RL measurements

Now let us consider the case when the femtocells make N RL measurements at time intervals of T_s seconds. The N measurements are averaged to reduce the effect of fading, and these averaged values are compared to decide the handoff target. The averaged values of RL power, $S_{1\text{avg}}(n)$ and $S_{2\text{avg}}(n)$ for femto 1 and 2 are given by,

$$\begin{aligned} S_{k\text{avg}}(n) &= \frac{\sum_{i=1}^N S_k(n - N + i)}{N}, \quad \text{for } k = 1, 2 \\ &= c + PL_0 - \frac{\sum_{i=1}^N F_0(n - N + i)}{N} \\ &\quad + \frac{\sum_{i=1}^N F_k(n - N + i)}{N}. \end{aligned}$$

Thus, the probability of error in choosing femto 1 as the active handoff target is

$$\begin{aligned} P_\varepsilon(\Delta, N) &= P\left(S_{1\text{avg}}(n) - S_{2\text{avg}}(n) < 0\right), \\ &= P\left(\frac{\sum_{i=1}^N F_2(n - N + i)}{N} - \frac{\sum_{i=1}^N F_1(n - N + i)}{N} > \Delta\right), \\ &= P\left(\frac{\sum_{i=1}^N H(n - N + i)}{N} > \Delta\right), \\ &= Q\left(\frac{\Delta}{\sigma_{H\text{avg}}(N)}\right). \end{aligned} \quad (12)$$

where $\sigma_{H\text{avg}}(N)$ is the standard deviation of

$$H_{\text{avg}}(n) = F_{2\text{avg}}(n) - F_{1\text{avg}}(n) = \frac{\sum_{i=1}^N H(n - N + i)}{N}$$

This value of $\sigma_{H_{\text{avg}}}(N)$ is evaluated using the auto-covariance of H in (9). Intuitively, we can expect probability of error to drop with an increase in the averaging duration N .

C. Probability of error with unsynchronized RL sensing

Till now we have assumed that the two femtocells start making RL measurements at the same sample index n . But as explained in section I, the RL sensing intervals may be unsynchronized. Let us consider a case where femto 2 starts making the RL measurement d samples later than femto 1. It is assumed that both the femtocells use the same averaging duration of N samples. Thus, the averaged RL signal strengths sensed by the two femtocells are given by,

$$S_{1\text{avg}}(n) = c + PL_0 - F_{0\text{avg}}(n) - PL_1 + F_{1\text{avg}}(n),$$

$$S_{2\text{avg}}(n-d) = c + PL_0 - F_{0\text{avg}}(n-d) - PL_2 + F_{2\text{avg}}(n-d).$$

An error in choosing Femto 1 as the handoff target occurs if the averaged RL strength, $S_{1\text{avg}}(n)$ is less than $S_{2\text{avg}}(n-d)$. The probability of this error is,

$$P_\epsilon(\Delta, N, d) = P\left(F_{2\text{avg}}(n-d) - F_{1\text{avg}}(n) + F_{0\text{avg}}(n) - F_{0\text{avg}}(n-d) > \Delta\right). \quad (13)$$

Since F_1 and F_2 are independent random variables, the variance of $(F_{2\text{avg}}(n-d) - F_{1\text{avg}}(n))$ is equal to variance of H_{avg} . In the previous case of synchronized sensing intervals, the $F_{0\text{avg}}(n)$ terms canceled out in difference $S_{1\text{avg}}(n) - S_{2\text{avg}}(n)$. But here the offset of d samples results in the addition of an additional variance $\sigma_x^2(N, d)$ to the total variance $\sigma_{\text{tot}}^2(N, d)$ of $S_{1\text{avg}}(n) - S_{2\text{avg}}(n-d)$.

$$\begin{aligned} \sigma_x^2(N, d) &= \text{Var}(F_{0\text{avg}}(n-d) - F_{0\text{avg}}(n)), \\ \sigma_{\text{tot}}^2(N, d) &= \sigma_x^2(N, d) + \sigma_{H_{\text{avg}}}^2(N). \end{aligned}$$

Thus, the expression for probability of error in (13) becomes

$$P_\epsilon(\Delta, N, d) = Q\left(\frac{\Delta}{\sigma_{\text{tot}}(N, d)}\right) \quad (14)$$

V. RESULTS

In this section the expressions of the probability of error (11), (12) and (14) are compared with simulation results. This comparison verifies the assumption of approximating sum of Rayleigh fading and shadowing as a Gaussian random variable. For simulation, we generate the correlated shadowing by passing white Gaussian noise through a single pole IIR filter. Rayleigh fading is generated using Jake's model in [4]. The choice of values of system parameters for fading and shadowing is given in Table I. The speed of the mobile is chosen as 1m/sec, average indoor pedestrian walking speed.

SYSTEM PARAMETERS	
Sample interval	$T_s = 1.25\text{ms}$
Velocity of the mobile	$v = 1\text{m/sec}$
Carrier frequency	$f_c = 2\text{GHz}$
Maximum Doppler frequency	$f_d = 6.67\text{GHz}$
Shadowing std. deviation and correlation distance for mobile-femtocell link	$\sigma_f = 6\text{dB}$ $d_{\text{corr}_f} = 2\text{m}$
Shadowing std. deviation and correlation distance for mobile-macrocell link	$\sigma_f = 6\text{dB}$ $d_{\text{corr}_m} = 10\text{m}$

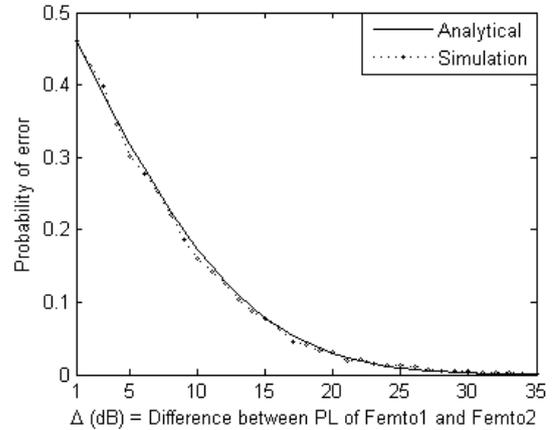


Fig. 3. Comparison of analytical and simulation plots of the decrease in probability of error with the Femto 1 and Femto 2 pathloss difference, Δ .

A. Probability of error with one RL measurement

Fig. 3 gives the analytical and simulation plots of the probability of error as a function of Δ . The error drops with increase in Δ because, larger the pathloss difference between the two femtocells, the fading cannot distort the RL measurements enough to result in Femto 2 being chosen instead of Femto 1. From Fig. 3 we can see that the probability of error becomes negligible for 30dB or more pathloss difference between the two femtocells.

B. Probability of error with multiple RL measurements

On averaging the RL sensed signal, the probability of error is lower than with instantaneous RL values. The decrease in error with Δ for different values of N is illustrated in Fig. 4. Fig. 5 illustrates the decrease in probability of error with N for $\Delta = 10\text{dB}$, 15dB and 20dB . System designers can choose an appropriate value of N to achieve a target probability of error for given value of Δ . For example, Fig. 5 shows that for $\Delta = 10\text{dB}$, an N of 300ms is sufficient to achieve less than 10 percent probability of error. This optimizes the tradeoff between probability of error and delay in handoff.

C. Probability of error with unsynchronized RL sensing

Now we analyze the effect of RL measurement offset d on the probability of error. Fig. 6 shows the plot of decrease in probability of error with Δ for various values of d . The averaging duration is chosen as $N = 250\text{ms}$. Fig. 7 illustrates the increase in probability of error with offset d for different values of $\Delta = 10\text{dB}$, 15dB and 20dB . For example, for the

$\Delta = 10\text{dB}$ curve, an offset of up to 300ms causes less than 3 percent increase in probability of error from 0.1 to 0.13. Thus, for a given Δ , N and offset d the increase in probability of error can be determined.

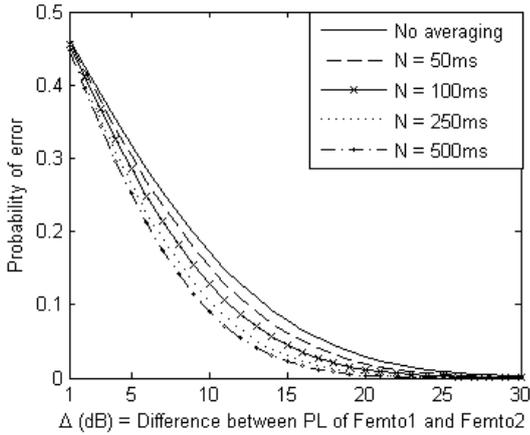


Fig. 4. Analytical plot illustrating the decrease in probability of error with Δ for fixed values of the averaging duration N .

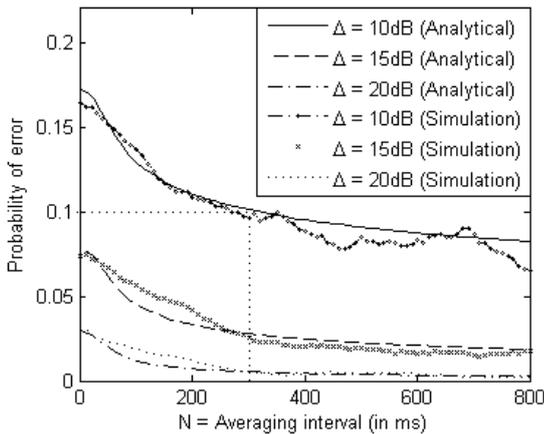


Fig. 5. Comparison of analytical and simulation plots of the decrease in probability of error with averaging duration N , for fixed $\Delta = 10, 15, 20\text{dB}$.

VI. CONCLUSIONS

The RL sensing method for active handoff in femtocells was analyzed in this paper. It is an effective method to resolve the ambiguity in choosing the target femtocell, which arises due to the high reuse of PN codes. However, fading and shadowing on the wireless links may lead to an incorrect decision of the handoff target. In this paper the tradeoff between probability of error and averaging duration was demonstrated. Using this tradeoff, a minimum averaging duration can be chosen to achieve a given bound on the probability of error. It was demonstrated that offset in RL measurement intervals result in a tolerable increase in probability of error. Cellular operators can use the design guidelines presented to optimize the femtocell handoffs.

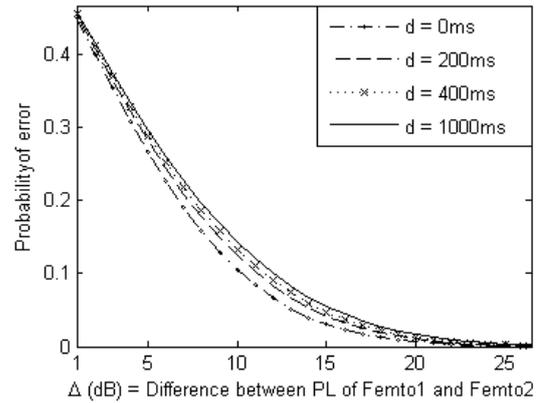


Fig. 6. Analytical plot illustrating the decrease in probability of error in handoff with increasing Δ for values of offset $d = 0, 200, 400$ and 1000ms . The RL averaging duration is chosen to be $N = 250\text{ms}$

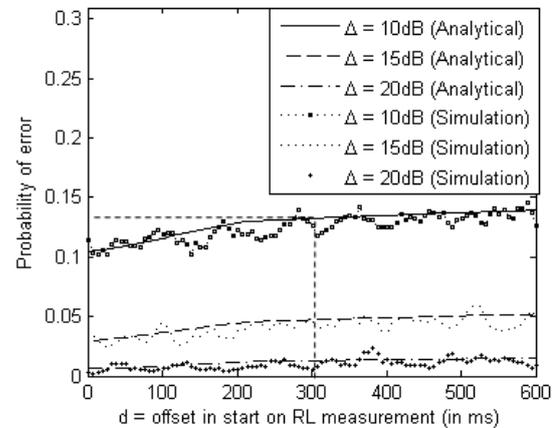


Fig. 7. Comparison of analytical and simulation plots of the increase in probability of error in handoff with offset d , for fixed $\Delta = 10, 15$ and 20dB .

ACKNOWLEDGMENTS

The first author would like to thank Prof. Abhay Karandikar and Prof. Animesh Kumar from IIT Bombay, India for helpful discussions on this work.

REFERENCES

- [1] Femto Forum, "Femto forum femtocell business case whitepaper." White Paper, June 2009.
- [2] V. Chandrasekhar and J. Andrews, "Femtocell networks: a survey," *IEEE Communications magazine*, vol. 46, pp. 59–67, Sept. 2008.
- [3] Airvana, "Femtocells: Personal base stations." White Paper, July 2007.
- [4] W. C. Jakes, *Microwave Mobile Communication*. Piscataway, NJ: Wiley IEEE Press, second ed., 1994.
- [5] A. M. D. Turkmani, "Probability of error for M-branch macroscopic selection diversity," in *Proc. IEEE Communications, Speech and Vision*, vol. 139, pp. 71–78, Feb. 1992.
- [6] M. Gudmundson, "Analysis of handover algorithms in microcellular radio," in *Proc. IEEE Vehicular Technology Conference*, pp. 537–542, May 1991.