Performance of hard handoff in 1xEV-DO REV A. systems with the presence of Rayleigh and correlated lognormal components*

Maher S. Al-Shoukairi
Dept. of Electrical and Computer Eng.
Texas A&M University
College Station, Tx 77843, USA
Email: maher@ece.tamu.edu

Khalid A. Qaraqe, Mohamed-Slim Alouini
Dept. of Electrical and Computer Eng.
Texas A&M University at Qatar
Education City, Doha, Qatar
Email:{khalid.qaraqe,alouini}@qatar.tamu.edu

Erchin Serpedin
Dept. of Electrical and Computer Eng.
Texas A&M University
College Station, Tx 77843, USA
Email: serpedin@ece.tamu.edu

Abstract—We analyze the performance of the hard handoff algorithm used in the 1xEV-DO Rev. A systems. A theoretical approach is presented to calculate the slot error probability (SEP). The approach enables us to evaluate the effects of filtering, hysteresis as well as the system introduced delay of handoff execution. Unlike previous work the model used considers multiple base stations (BS) and accounts for correlation of shadow fading affecting different signal powers received from different BS’s. The theoretical results are verified over ranges of parameters of practical interest using simulations which are also used to evaluate the packet error rate (PER) and the number of handoffs.

Keywords— Cellular systems, seamless handoff, cdma2000, 1xEV-DO, performance analysis.

I. INTRODUCTION

1xEV-DO Rev. A systems use a Data Source Channel (DSC) to allow for seamless handoff between base stations (BS). The mobile station (MS) uses the DSC to provide an indication ahead of time of the change in the serving BS. The knowledge of the exact time at which the change of serving BS occurs minimizes the transition delay and allows the MS to be served by only one BS at all times. However the delay in handoff execution holds the MS from being served by the BS providing it with the best signal reception, causing possible degradation of service quality. Hence the analysis of different factors affecting the handoff performance is required especially since 1xEV-DO Rev. A systems are expected to provide delay sensitive services such as voice-over-IP (VOIP) and multiplayer gaming.

Handoff performance was analytically studied by Vijayan and Holtzman [1] where they considered the effect of averaging and hysteresis on the handoff process. Their work was further improved in [2]. The sensitivity of soft and hard handoff algorithms to the delay in the handoff execution was studied in [3], and recently [4] used an analytical approach to evaluate the performance in 1xEV-DO Rev. A systems taking into consideration several factors affecting the handoff algorithm. However although unlike most analytical approaches, [4] considered the effects of the Rayleigh fading and handoff execution delay, its system model like most previous work considered only two base stations neglecting the interference caused by the neighboring base stations as well as the possibility of a handoff to one of them. Moreover shadow fading components affecting different received signals from different base stations were assumed to be independent, while in practice due to the fact that the power received at the MS from different BS’s will probably be shadowed by the same obstacles surrounding the MS it is more accurate to assume that the lognormal components are correlated. We develop an analytical approach to evaluate the slot error probability (SEP) due to Rayleigh and correlated shadow fading, system delays and hysteresis while adopting a multiple BS’s model. The performance is also studied through the packet error rate (PER) and number of handoffs that are both obtained through simulations, since it is very complex to theoretically evaluate the PER knowing that the system employs hybrid automatic repeat request (H-ARQ) [5].

II. SYSTEM MODEL

The MS is assumed to be at equal distance from four BS’s as shown in Fig. 1. At any point of time the MS will be connected to one of the four BS’s, while the rest are considered to be interferers. Moreover the case of noiseless interference limited transmission is considered.

Fig. 1. The Four-Cell Model
Handoff decisions are based on the signal to interference ratios obtained from the measured signal strengths of the pilots in the received slots, therefore the slot period is used as the system sampling time (T_s=1.667ms) for our discrete time analysis. The power of the signal received from BS_i (in decibels) is represented in [6] as
\[ P_i = Y_i(n) + 10 \log_{10} \left( X_i(n)^2 \right). \] (1)

Where \( Y_i(n) \) represents the combination of the path loss component (L_i) and the shadow fading component (W_i(n)), \( Y_i(n) \) is a normally distributed random process with mean \( L_i \) and standard deviation \( \sigma_{Y_i} \). In (1) \( X_i(n) \) represents the Rayleigh fading component and is assumed under narrowband and frequency flat fading conditions.

A correlation of 50% between shadow fading components affecting transmitted signals from different BS's is suggested by [5], while the Rayleigh fading is assumed to be independent from the shadowing as well as independent between different BS's. The shadow fading is modeled as a first order autoregressive random process with the auto-covariance function
\[ R(n) = i \quad F_i(n) - F_{\text{max}_i}(n) \geq H \]
\[ = R(n-1) \quad \text{otherwise}, \] (6)

where \( F_{\text{max}_i}(n) \) is max\( \{ F_j(n) \} \) and \( R(n)=i \) is the request at time \( n \) to connect to BS_i.

The filter used is a first order low pass filter with the impulse response [4]
\[ h(n) = \left(1/T_{ir}\right) \left(1 - 1/T_{ir}\right)^n, \] (7)

where \( T_{ir} \) is the filter constant.

### IV. ERROR PROBABILITY

By definition a slot error is assumed to occur if the received SIR drops below a specified threshold (T), this means that a slot error occurs if BS_i is serving the MS and \( S_i(n) < T \) yielding
\[ SEP = \sum_{i} \int_{-\infty}^{T} f(S_i(n), C(n) = i) dS_i, \] (8)

where \( f(S_i(n), C(n) = i) \) is the joint probability density function of \( S_i(n) \) and \( C(n) \) and \( C(n) = i \) denotes that the MS is being served by BS_i at time i. \( C(n) \) is introduced to compensate for the delay \( k \) imposed by the system between a handoff request \( R(n-k) \) and the connection based on that request \( C(n) \). This delay was found in [4] to be 1.5 to 2.5 (DSCLength).

To find \( f(S_i(n), C(n) = i) \) we follow an approach similar to that in [3] and [4]:

Defining \( FS_i = F_i - F_{\text{max}_i} \) and changing the representation of the time indices to subscripts we can write
\[ f(S_i | C_n = i) = f(S_{ia} | R_{ia} = i) \]
\[ = \int f(S_{ia} | R_{ia} = i) | FS_{ia}(n-k) | f(FS_{ia}(n-k)) dFS_{ia}(n-k) \] (9)

\[ f(S_{ia} | R_{ia} = i) | FS_{ia}(n-k) | = \gamma f(S_{ia} | FS_{ia}(n-k)) | FS_{ia}(n-k) \leq H \] (10)

where \( \gamma \) is the probability of (\( | FS_{ia}(n-k) | \leq H \) and \( C_n = i \))

\[ f(S_{ia} | C_n = i) = \int_{-H}^{H} f(S_{ia} | FS_{ia}(n-k)) dFS_{ia}(n-k) \]
\[ + \gamma \int_{-H}^{H} f(S_{ia} | FS_{ia}(n-k)) dFS_{ia}(n-k). \] (12)

To evaluate (12) some approximations are made to keep the analysis tractable.

The combined Rayleigh lognormal distribution can be approximated by another lognormal distribution [8]. This approximation is considered reasonable for values of the standard deviation of the lognormal greater than 6 dB, where
for the 1xEV-DO REV. A. systems the suggested value in [5] is 8.9 dB. The mean and standard deviation of the combination are given by

\[ M_{p_i} = L_i - 2.5dB, \quad \sigma_{p_i} = \sqrt{\sigma_{Y_i}^2 + 5.57^2}. \] \hspace{1cm} (13)

The correlation between the different powers received from different BS’s can be found by using equations from [9]

\[ \rho_{M_iM_j} = \frac{\text{cov}(P_{M_i}, P_{M_j})}{\sigma_{M_i}\sigma_{M_j}} \] \hspace{1cm} (14)

\[ M_{p_i} = M_{Y_0} = \exp(\lambda M_{Y_i} + \frac{\lambda^2}{2} \sigma_{Y_i}^2), \] \hspace{1cm} (15)

\[ \text{cov}(P_{Y_i}, P_{Y_j}) = (\rho_{Y_iY_j}, \sigma_{Y_i}, \sigma_{Y_j}, M_{Y_i}, M_{Y_j})e[X_i^2X_j^2] - M_{Y_i}M_{Y_j} \] \hspace{1cm} (16)

\[ \rho_{Y_iY_j} = \frac{\exp(\lambda^2 \rho_{Y_iY_j}, \sigma_{Y_i}, \sigma_{Y_j})-1}{\exp(\lambda^2 \sigma_{Y_i}^2 - 1)(\exp(\lambda^2 \sigma_{Y_j}^2 - 1))} \] \hspace{1cm} (17)

\[ \sigma_{Y_i}^2 = \exp(2\lambda M_{Y_i} + \lambda^2 \sigma_{Y_i}^2)(\exp(\lambda^2 \sigma_{Y_i}^2) - 1), \] \hspace{1cm} (18)

where \( Y_0 \) is the mean and standard deviation of \( Y_i \) and \( M_{p_i} \) and \( \sigma_{p_i} \) are the mean and standard deviation of \( P_{M_i} \).

Using the technique developed by Schwartz and Yeh and extended in [10] to approximate the linear sum of correlated lognormal distributions again with a lognormal, the distribution of \( N^\Sigma M_{p_i} \) is considered to be normal with mean

\[ E[10^{4/10}10^{B/10}] = \sum_{i=1}^{N} \sum_{j=1}^{M} e^{\lambda M_{M_i} + \lambda M_{M_j} + \frac{1}{2} \lambda^2 (\sigma_{M_i}^2 + \sigma_{M_j}^2 + 2\rho_{M_iM_j}\sigma_{M_i}\sigma_{M_j})}. \] \hspace{1cm} (21)

Then again from [9]

\[ \rho_{AB} = \frac{\lambda^2 \sigma_{M_i}\sigma_{M_j}}{E[M_{M_i}M_{M_j}]} \] \hspace{1cm} (22)

To find the auto-covariance and cross-covariance functions between different \( S_i \)’s an extension to the Wilkinson’s approach is used [12]

\[ R_{X_i^2} (l) = E[X_i^2(n)X_i^2(n+l)] = J_k^2(2\pi f_T l) + 1 \] \hspace{1cm} (23)

\[ C_{Y_iY_j} (l) = \rho_{Y_iY_j} C_{Y_iY_j} (l) \] \hspace{1cm} (24)

\[ R_{X_i^2X_j^2} (l) = E[X_i^2(n)X_j^2(n+l)] = 10^{Y(n)/10}10^{Y(n+l)/10}] \] \hspace{1cm} (25)

\[ R_{P_{p_i}P_{p_j}} (l) = R_{X_i^2X_j^2} (l)E[10^{Y(n)/10}10^{Y(n+l)/10}] \] \hspace{1cm} (26)

where \( P_{A} = X_i^2 Y_i^2 \).

Again in general if

\[ A = 10\text{log}_{10}(10^{P_{i,10}} + 10^{P_{i,10}} \ldots \ldots 10^{P_{i,10}}) \]

\[ B = 10\text{log}_{10}(10^{P_{i,10}} + 10^{P_{i,10}} \ldots \ldots 10^{P_{i,10}}) \]

Then

\[ E[10^{4(n)/10}10^{B(n+l)/10}] = \sum_{i=1}^{N} \sum_{j=1}^{M} R_{X_i^2X_j^2} (l)e^{\lambda M_{M_i} + \lambda M_{M_j} + \frac{1}{2} \lambda^2 (\sigma_{M_i}^2 + \sigma_{M_j}^2)} \] \hspace{1cm} (27)

\[ C_{AB} (l) = \frac{1}{\lambda^2}[\text{ln}(E[10^{4(n)/10}10^{B(n+l)/10}])] - \lambda M_{M_i} + \frac{1}{2} \lambda^2 (\sigma_{M_i}^2 + \sigma_{M_j}^2)] \] \hspace{1cm} (28)

\[ C_{S_{i,j}} (l) = C_{p_{i,j}} (l) - C_{p_{i,j}} (l) - C_{p_{i,j}} (l) + C_{p_{i,j}} (l) \] \hspace{1cm} (29)

where the covariance functions in (29) are evaluated using (28).

Passing the \( S_i \)’s through the averaging filters we get

\[ M_{F_i} = E[F_i] = M_{S_i} \] \hspace{1cm} (30)

\[ C_{F_{i,j}} (l) = C_{S_{i,j}} (l) = h(l) * C_{S_{i,j}} (l) \] \hspace{1cm} (31)
\[ C_{FF_i}(l) = h(l) \ast h(-l) \ast C_{S_i}(l), \]  

(32)

where \( h(l) \ast h(-l) = (1/T_{ir}) \ast (1 - 1/T_{ir}) \).

To find the distribution of \( F_{\text{max}} \), the Clark’s approach is used. The approach approximates the maximum of a group of normal distributions by another normal distribution, the approach starts by matching the moments of a new normal distribution to that of the maximum of only two, then the same procedure is repeated using a pair at a time. Clearly the approximation is more accurate for the case of a small number of random processes (three in this case), since the increasing number of random processes will increasingly affect the accuracy of the assumption of the maximum being normally distributed.

The mean \( M_{F_{\text{max}}} \) and standard deviation \( \sigma_{F_{\text{max}}} \) of \( F_{\text{max}} \) are found using the Clark’s approach, which leads to

\[
M_{FS_i} = M_F - M_{F_{\text{max}}}, \sigma^2_{FS_i} = \sigma^2_F + \sigma^2_{F_{\text{max}}} - 2 \rho_{F_{F_{\text{max}}}} \sigma_F \sigma_{F_{\text{max}}} \]

(33)

\[
\rho_{FS_i} = (\rho_{F_{F_{\text{max}}}} \sigma_F \sigma_i - \rho_{F_{F_{\text{max}}}} \sigma_{F_{\text{max}}} \sigma_i)/(\sigma_{FS_i} \sigma_i), \]

(34)

where \( \rho_{F_{F_{\text{max}}}}, \rho_{FS_i}, \rho_{F_{F_{\text{max}}}S_i} \) and \( \rho_{F_{F_{\text{max}}}(i-k)}S_i \) are calculated using the same technique used in the Clark’s approach to calculate the correlation between the approximation of the max of two processes and a third process.

Finally \( \gamma \) can be calculated using the following equation

\[
P(C_n = i) = P(F_{S_i} > H) + \gamma P(F_{S_i} < H) \]

(35)

and since the MS is at equal distance from all BS’s and since all \( P_i \)'s are identically distributed \( P(C_n = i) = 1/4 \) and the final slot error probability is

\[
SEP = 4 \int_{-H}^H f(S_i(n), F_{S_i (n-k)}) dF_{S_i (n-k)} dS_i
\]

\[
+ \gamma \int_{-H}^H f(S_i(n), F_{S_i (n-k)}) dF_{S_i (n-k)} dS_i. \]

(36)

\[ V. \hspace{0.1cm} \text{RESULTS} \]

To confirm the accuracy of our approach over parameters of practical interest computer simulations were used with the slot duration as the sampling period. A first order autoregressive model was adopted to simulate shadow fading with decorrelation distance of 20m, and the Jake’s simulation model was used to simulate Rayleigh fading. The carrier frequency was chosen to be 1.9 Ghz, a threshold (\( T \)) of -15 dB and a hysteresis (H) of 2 dB were used. On the other hand analytical based results were obtained using (36).

A comparison between numerical and simulated results using the cumulative distribution function (CDF) of the SIR received at the MS is shown in Fig. 2. This CDF was obtained by varying the value of \( T \) in (36). The figure shows that the numerical values of the SEP match closely the simulated ones with increasing accuracy for higher MS speed. Hence in subsequent figures only the numerical results are shown for the SEP.

Since 1xEV-DO systems transmit at different data rates with different packet lengths (1-16 slots), and since it also uses H-ARQ which requires multiple slot packets to be transmitted with 4-slot interleaving giving the receiver enough time to decode the received packet and send a response we use the technique explained in [15] for PER simulations. In this technique when a new packet slot is received the linear average SIR is calculated for the new slot along with all previous slots from the same packet. Based on this average SIR a lookup table (that is previously generated from link level simulations) is used to calculate the PER, using this PER we pseudo-randomly determine if the packet is in error. This process is repeated until the packet is assumed to be decoded with no errors or the maximum number of slots for that packet is received. In subsequent figures the PER was simulated for a data rate of 34.8 kbps which uses a 16 slot packet.

The effect of the system introduced delay represented by the DSC channel length along with the effect of the filter constant \( T_{IR} \) on some chosen system performance measures are shown in figures 3-5 for different MS speeds.

At low speeds when the system delay is minimal (DSC length is equal to 1) a lower \( T_{IR} \) means better tracking of the relatively slowly varying Rayleigh fading and hence lower SEP. As \( T_{IR} \) increases the ability of tracking the Rayleigh fading variations decreases causing the SEP to increase. But as the system introduced delay increases this close tracking of the Rayleigh fading variations becomes a disadvantage, since by the time a requested handoff is executed the SIR will have moved to a new state. Therefore more filtering is advantageous since it filters out fast SIR changes with which the system is unable to catch up.

At medium speeds the relatively fast variations of the Rayleigh fading are filtered out. Moreover the shadow fading is slowly changing and can be generally tracked using any of the suggested \( T_{IR} \)'s, therefore the increase of SEP with increasing \( T_{IR} \) is caused by the increase of filtering delays. This increase is more noticeable for small DSC lengths since at large DSC...
measures at MS speed of 80 m/s

these variations, SEP is expected to increase when T_IIR is
to be filtered out. However shadowing variations will increase,
At higher speeds Rayleigh fading variations are still assumed
filtering and contributes more to the increase of SEP.

lengths the system introduced delay is greater than that of the
filtering and contributes more to the increase of SEP.
At higher speeds Rayleigh fading variations are still assumed
to be filtered out. However shadowing variations will increase,
and since smaller filter constants allow for better tracking of
these variations, SEP is expected to increase when T_IIR is
increased at different DSC lengths.

The figures also show that the number of handoffs
decreases with an increasing T_IIR since less fluctuation in the
filtered SIR’s will result in longer operating times for each BS
before a handoff is initiated. Moreover it also shown that the
number of handoffs slightly decreases with increasing DSC
length, since recurring delays in the handoff execution will
eventually result in a less overall number of handoffs.

We can also conclude from the proceeding figures that
although for a packet switched system (as the one being studied) the PER is a more important measure for system
performance, when studying the effects of different parameters
on the handoff performance the insight gained from the SEP or
the PER is generally the same.

VI. SUMMARY

A theoretical framework to evaluate the handoff
performance was presented in this paper. While considering
the effects of Rayleigh fading and correlated shadowing, and
adopting a multiple BS system model, effects of different
system parameters as filtering as well as system delay on the
overall performance were discussed. The system performance
was basically studied through numerical results of slot error
probability and simulated ones for the number of handoffs and
packet error rate. Different tradeoffs between these
performance measures were shown as well.

REFERENCES


4924-4929.

[5] 3GPP2 TSG-C WG3 “1xEV-DO Evaluation Methodology,” 3GPP2


15-17, Jan 2000.


fading in mobile radio systems,” IEEE Communication Letters, vol.3,

of on-off log-normal processes with wireless applications,” to appear in

1701-1705.