Multipath Diversity Reception of Wireless Multiple Access Time-Hopping Digital Impulse Radio

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ABSTRACT

Performance of multiple access spread spectrum time-hopping digital impulse radio with pulse position data modulation under multipath propagation conditions is analytically investigated. To simplify the mathematical complexity associated to derivation of the SNR, we assume independent identically distributed random delay for each arriving path of each user. Specifically, the multipath arrival times are uniformly distributed over one frame period. This assumption along with restricting the time-hopping range to a fraction of a frame duration leads to a closed form solution of SNR. Using this result, degradation factor due to multiple access interference in the presence of multipath is derived and curves for two special cases of exponentially decaying and flat multipath channels are sketched. To investigate the more realistic delay spread profiles, we show simulation results for exponentially decaying and flat multipath channels with deterministic multipath arrival times.

1. INTRODUCTION

Multiple access capacity and performance of digital impulse radio under ideal propagation conditions, where there is only one path between each user's transmitter and the user of interest's receiver, under perfect power control has been investigated [1], [2]. In this paper, we investigate the performance under more realistic propagation conditions, where there are many paths between each transmitter and the receiver of the user of interest. Signals transmitted by different users experience different channels depending on the position of each user. To avoid multiple access collisions, each user is assigned his/her own time-hopping code; however, we assume that the multiple selective combining receiver of the user of interest perfectly knows and is synchronized to the time-hopping code of the user of interest. Exponentially decaying multipath channel is an example of when the amplitudes are decaying very fast unlike the flat multipath case, where each path in the multipath is as significant as others. For the case of exponentially decaying multipath channel, we assume the last path of the delay spread profile is 30 dB lower in power than the strongest path. Degradation factor is introduced and computed under different system performance and numbers of selected dominant paths [3].

In Section II, the analysis of the multiple selective combining receiver leads to the derivation of the operating SNR. Degradation factor due to multiple-access in the presence of multipath is discussed in Section III. Simulation results for deterministic multipath channels are given in Section IV. Using this kind of simulation, we can predict the performance of time-hopping digital impulse radio under any arbitrary multipath pattern for each user. Conclusion remarks are made in Section V.

2. RECEIVER PROCESSING

Assuming N_u active users communicating through the multiple access time-hopping impulse radio, each experiencing a different channel, and considering the first L^k dominant paths for the kth user, the received signal is

$$r(t) = \sum_{k=1}^{N_u} \sum_{m=0}^{L^k-1} g_m^k S_{rec}^k(t - \tau_m^k) + n(t) \qquad (1)$$

where g_m^k denotes the amplitude of the mth path of the kth user. Also, τ_m^k accounts for its corresponding independent random delay relative to τ_0^1. Therefore, without loss of generality, we assume $\tau_0^1 = 0$. The received signal of user k with no delay with respect to the line of sight path signal of the user of interest (User 1) is denoted by $S_{rec}^k(t)$. The additive white

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Gaussian noise, $n(t)$, is assumed to have a two-sided power spectral density of $\frac{N_0}{2}$ and

$$S_{rec}^k(t) = \sum_j w_{rec}(t - jT_f - c_j^k T_c - \delta D_j^k) \qquad (2)$$

where $w_{rec}(t)$ is the received mono-cycle [1]. Each data symbol is transmitted repeatedly in N_s consecutive frames in order to attain diversity and make soft decisions at the receiver. Therefore, $D_{iN_s}^k = D_{iN_s+1}^k = ... = D_{(i+1)N_s-1}^k = d_i^k$ for all i's and $k = 1, 2, ..., N_u$. Here d_i^k is the ith transmitted symbol of user k and D_j^k is the ith repeated transmitted symbol of user k in the jth frame for $j = iN_s, iN_s+1, ..., (i+1)N_s-1$. In each frame period T_f, one pulse is transmitted. The position of the pulse in each frame is determined by the time-hopping pattern of user k in the jth frame, c_j^k, and the pulse position data modulation parameter δ. The time-hopping codes are assumed random and independent. Each frame is divided into several time slots with duration T_c. For a complete description of all the parameters used here, the reader may refer to [1] and [2].

Assuming a multiple selective combining receiver, the P dominant paths of the user of interest are selected [3], and each is processed in a separate branch of the RAKE receiver shown in Fig. 1. The following correlation is made at the branch corresponding to the qth selected path:

$$A_q(i) = \int_{t=iN_sT_f+\tau_q^1}^{(i+1)N_sT_f+\tau_q^1} r(t) \sum_{j=iN_s}^{(i+1)N_s-1} g_q^1 v(t - jT_f - c_j^1 T_c - \tau_q^1)\, dt \qquad (3)$$

where $v(t) = w_{rec}(t) - w_{rec}(t-\delta)$ is the template waveform used at the receiver [1]. If $A(i) = \sum_{p=1}^{P} A_{q_p}(i)$ is greater than zero we decide in favor of H_0, that is, the transmitted symbol d_i^1 has been a zero, otherwise we decide the hypothesis H_1. It is worth noting that in all the above signal processing, we have assumed that the receiver has locked to the first user's time hoping code and it knows the delays of the selected paths. Writing $\tau_m^k - \tau_q^1 = \alpha_{m,q}^k T_f + \beta_{m,q}^k$ where α is an integer and β is a uniformly distributed random variable over $[-T_f/2, T_f/2]$ and assuming $\frac{T_f}{2}$ to be much greater than δ and with careful inspection of the integral and summation intervals, considering:(1) $w_{rec}(t) = 0$ for $t < 0$, or $t > T_m = 0.7$ ns, (2) $T_m > \delta$, and (3) $|c_j^p - c_l^q| T_c < 0.5T_f - 2T_m - \delta$, we can conclude

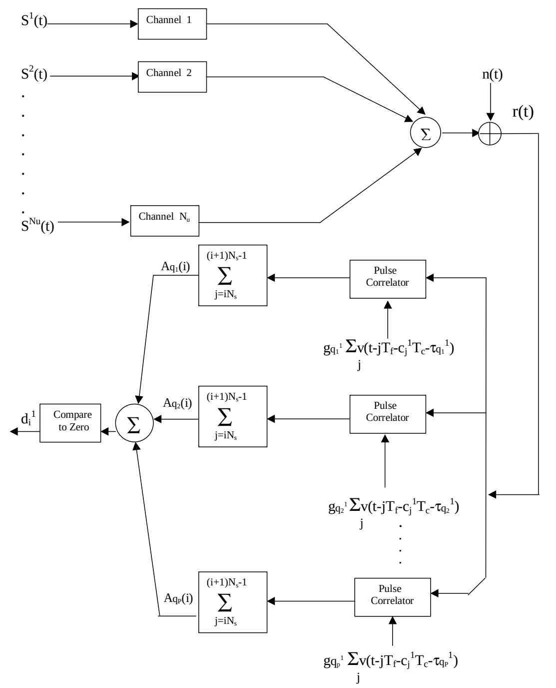

Figure 1: Block diagram of the multiple selective combining RAKE receiver

$$A_q(i) = N_s {g_q^1}^2 R_{vw_{rec}}(\delta d_i^1) \sum_{j=iN_s}^{(i+1)N_s-1} \sum_{k=1}^{N_u} \sum_{m=0 (k=1, m\neq q)}^{L^k-1} g_q^1 g_m^k R(\delta D^k_{j-\alpha^k_{m,q}} + \beta^k_{m,q} - (c_j^1 - c^k_{j-\alpha^k_{m,q}})T_c) + N_s g_q^1 \int_{-\infty}^{\infty} n(t)v(t)dt \qquad (4)$$

where $R_{vw_{rec}}(\tau) = \int_{-\infty}^{\infty} v(t) w_{rec}(t-\tau)dt$ is the cross-correlation between the template waveform $v(t)$ and the received mono-cycle $w_{rec}(t)$ and can have non-zero values only on the interval $[-T_m, T_m+\delta]$, because the support of $v(t)$ is $[0, T_m+\delta]$.

We leave the derivation of SNR at the input of the threshold comparator $(A(i))$ to the interested reader, and just give the following results. Signal energy contained in the selected paths of the user of interest is given as

$$E_s = {N_s}^2 \Big(\sum_{p=1}^{P} {g_{q_p}^1}^2\Big)^2 R^2_{vw_{rec}}(0) \qquad (5)$$

The variance of the zero-mean interferences arising from multiple access and non-selected paths of the user of interest, using the central limit theorem, is given by

$$P_I = \frac{N_s}{T_f} \sum_{p=1}^{P} \sum_{k=1}^{N_u} \sum_{m=0 (k=1, m \neq q_p)}^{L^k - 1} (g^1_{q_p} g^k_m)^2 \int_{-\infty}^{\infty} R^2_{vw_{rec}}(x) dx \qquad (6)$$

Also, the variance of the terms due to AWGN is

$$\sigma_n^2 = {N_s}^2 \Big(\sum_{p=1}^{P} g^1_{q_p}\Big)^2 \frac{N_0}{2} \int_{-\infty}^{\infty} v^2(t) dt \qquad (7)$$

From (5), (6), and (7), the SNR is

$$\mathrm{SNR}(N_u) = \frac{{N_s}^2 \big(\sum_{p=1}^{P} {g^1_{q_p}}^2\big)^2 R^2_{vw_{rec}}(0)}{\mathrm{Den}} \qquad (8)$$

where

$$\mathrm{Den} = P_I + {N_s}^2 \Big(\sum_{p=1}^{P} g^1_{q_p}\Big)^2 \frac{N_0}{2} \int_{-\infty}^{\infty} v^2(t) dt \qquad (9)$$

and $\mathrm{SNR}(N_u)$ explicitly implies the operating SNR in the presence of N_u active users. Equation (8) simplifies to equation (2.28) in [2] under ideal propagation conditions and perfect power control.

3. DEGRADATION FACTOR

Degradation Factor, $DF(N_u; L^1, L^2, ..., L^{N_u}) = 10\log(\frac{\mathrm{SNR}_{(1;1)}}{\mathrm{SNR}_{(N_u; L^1, L^2, ..., L^{N_u})}})$ is a measure of degradation in the operating SNR as the number of active users with L^k paths between User k's transmitter and User 1's receiver increase. We can also think of it as the additional required power in dB that is needed in order to maintain the same performance as the number of users with L^k paths for User k increases from one to N_u. In order to evaluate the degradation factor caused solely by multipath at a fixed number of users, we can compute $DF(N_u; \mathbf{L}_1) - DF(N_u; \mathbf{L}_2)$ where $\mathbf{L}_i$ accounts for a particular situation of assigning paths to different users. Figures 2 and 3 show the degradation factor of N_u users for two cases where for the first case we have assumed g^k_m is exponentially decaying for each user with its weakest path 30 dB lower in power than its strongest path. As another extreme, we have assumed flat multipath channels for all users where the strength of each path is the same for all the received paths. For both cases, we have also assumed $L^k = L = 100$ and $g^k_0 = 1$ for any k. Curves of Fig. 2 are drawn at bit error rates of $P_e = 10^{-3}$, $P_e = 10^{-4}$, and $P_e = 10^{-5}$ when the transmission rate is fixed at $R_s = 1$ Mbps.

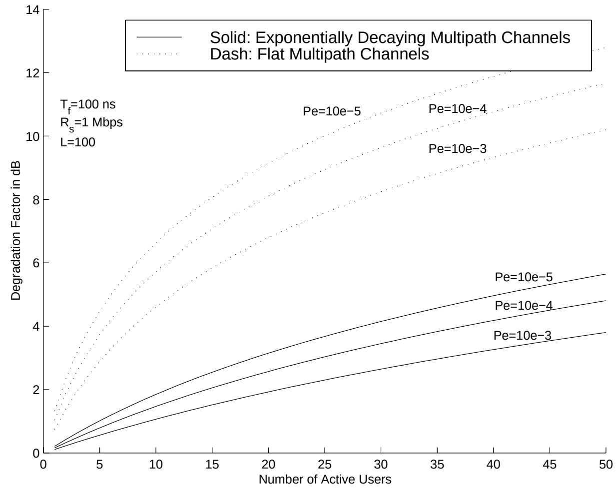

Figure 2: Degradation Factor for different bit error rates at 1 Mbps

Using a frame of duration 100 ns suggests that we are sending $N_s = 10$ pulses per symbol. As Fig. 2 shows, degradation factor increases with better bit error rates, since we need more power to accommodate the same number of users with a better quality of service at the same transmission rate. However, the degradation factor is much larger for flat multipath compared to that of exponentially decaying channels, because at the same receiver's selectivity order, the energy contained in the unselected paths of the flat channel is much more than those contained in the exponentially decaying channel, therefore, they contribute as more powerful interference power causing a poorer performance. Curves of Fig. 2 are sketched for the case when receiver selects the strongest path of the user of interest only. Fig. 3 shows the degradation factor for both exponentially decaying and flat channels at $P_e = 10^{-3}$ and $R_s = 10$ Mbps when different numbers of received dominant paths of the user of interest are selected at the receiver [3]. As can be seen from Fig. 3, degradation factor decreases as the selective combining receiver chooses more and more paths of the user of interest's received signal. In Section IV, we will see that this decrease may not be necessarily true for more realistic multipath patterns. The reason for this decrease here, is due to the fact that we assumed uniformly distributed over one frame duration path arrival delays for each user. Assuming purely unifromly distributed path arrival delays along with purely random time-hopping codes reduces the chance of selected paths being corrupted, therefore, helps the receiver collect more signal energy, hence, smaller degradation factor.

4. Simulation Results

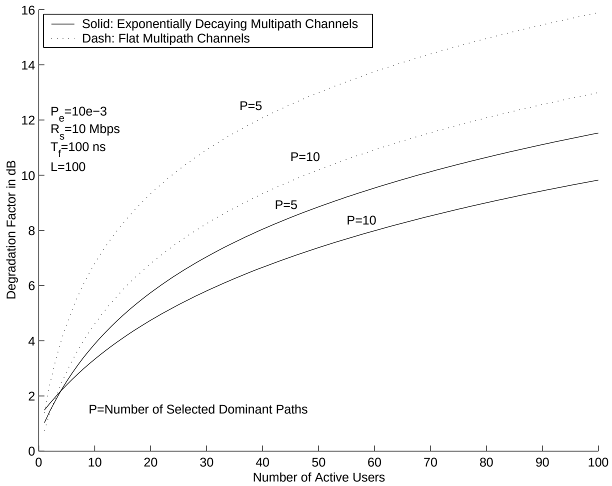

Figure 3: Degradation Factor for different numbers of selected dominant paths

Analysis being done so far, led to a closed form mathematical equation for multiple access SNR in the presence of multipath, when the arrival times of each user's multipath were uniformly distributed over a frame duration. Fig. 4 shows the theoretical and simulation results for bit error rate versus the number of active users for this situation using random time-hopping codes. It is reasonable to assume uniformly distributed asynchronous delays between different users over a frame duration; however, assuming uniformly distributed path arrival delays over a frame period for each active user might not be valid in some practical cases. Therefore, we conduct simulations for more complex situations where solving the problem analytically may not be feasible. For this reason, we again simulate exponentially decaying and flat multipath channels when asynchronous delays between different users are uniformly distributed over a frame period; however, each path comes after another under a deterministic delay profile. Also, instead of random time-hopping codes, we implement codes with favorable correlation properties [4]. As a dense multipath environment, we assume each path comes 0.5 nanosecond after the previous one, and we neglect paths whose powers are 30 dB lower than the strongest path. Fig. 5 shows how bit error rate degrades as the delay spread profile increases for all the users. For all the curves given, we have assumed the same channel for each user, but with different asynchronous delays with respect to the user of interest. At each frame duration, the performance becomes poorer as the delay spread profile or the number of active users increases and we need to use longer frame durations in order to accommodate more number of users at harsher delay spread profiles. Using longer frame periods helps us mitigate the chance of strong collisions. Fig. 6 compares the performance of exponentially decaying and flat multipath channels at the same frame duration and number of users versus delay spread. As can be seen, the performance for flat multipath channels are orders of magnitude worse than exponentially decaying channels. Flat multipath case can be assumed as the worst case scenario, and we can use it as a marginal analysis tool. If we design the system such that it gives satisfactory results for flat multipath case, then any better scenario will lead to a better result.

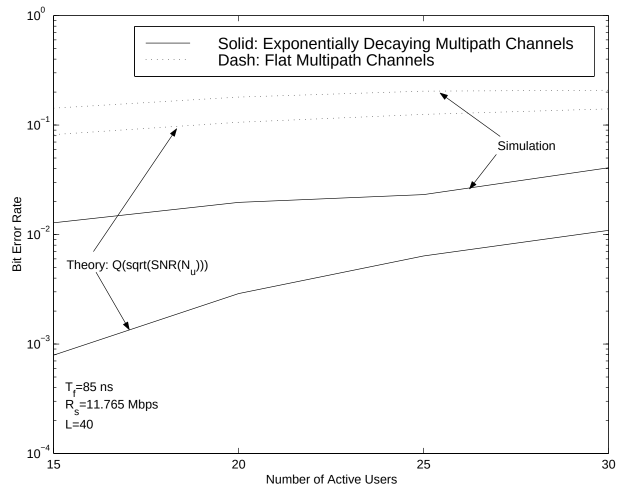

Figure 4: Theoretical and simulation results for bit error rate versus the number of active users

In Fig. 7 the effect of selective combining receiver and different hopping ranges are illustrated. For figures 4, 5, and 6, the receiver is choosing the strongest path of the user of interest only. As can be seen, selecting more paths does not necessarily lead to a better performance. This is due to the fact that we are adding corrupted paths which degrades the soft decision performance. If users are distributed sparsely over the frame period, then selecting more paths should improve the performance, otherwise selecting more corrupted paths will corrupt the decision statistic.

Restricting the hopping range to a fraction of a frame duration may improve the system performance since collisions arising from some of the users delayed asynchronously apart enough will be omitted; however, for the rest of the users whose asynchronous delays with respect to the user of interest are small, the chance of collisions may increase due to a more limited hopping range. In general, restricting the hopping range may improve or degrade the performance depending on the distribution of the asynchronous delays between each user and the user of interest. For synchronous or relatively synchronous users, restricting the hopping range will result in more collisions and worse performance.

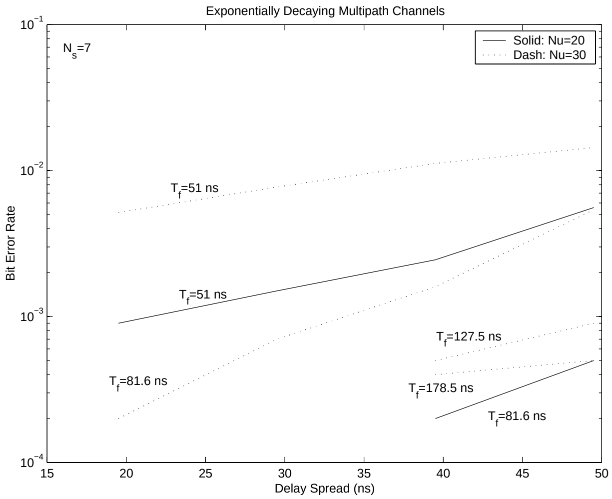

Figure 5: Bit error rate versus delay spread at different frame durations

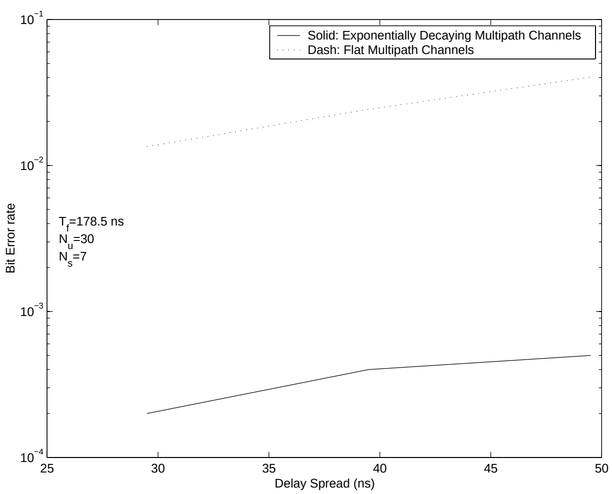

Figure 6: Bit error rate versus delay spread for exponentially decaying and flat multipath channels

5. CONCLUSION

Performance of multiple access digital impulse radio in the presence of multipath using a multiple selective combining RAKE receiver was analytically investigated. Degradation factor for exponentially decaying and flat multipath channels show that at any bit error rate, data rate, or number of selected dominant paths, the performance with flat multipath channels degrade much more than that of exponentially decaying multipath channels. Flat multipath channels can be used

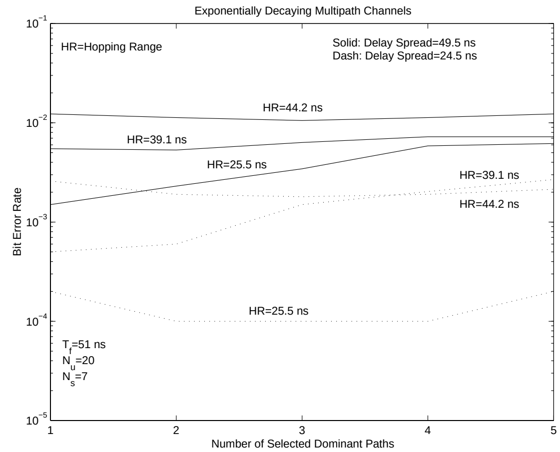

Figure 7: Bit error rate versus the number of selected dominant paths at different delay spreads and hopping ranges

as a marginal analysis tool corresponding to the worst performance scenario. Simulation results for more sophisticated realistic situations show how performance depends on the delay spread profiles, frame durations, or number of active users. Depending on the asynchronous delays between each user and the user of interest, restricting the hopping range may improve or degrade the performance. Selecting more paths of the user of interest at the receiver when users are sparsely distributed over the frame duration improves the performance, otherwise selecting more corrupted paths will severely corrupt the decision statistic for making soft decisions on the transmitted data.

References

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