A Wireless Packet Multiple Access Method Exploiting Joint Detection\textsuperscript{1}

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Abstract

A new packet-based, multiple access scheme for connectionless, uncoordinated random access is proposed using code-division multiple access (CDMA) as the physical access method, and exploiting the use of a multiuser detector at the receiver. The new method uses a novel packet format with a common header with identical spreading codes for all users and packets, and random spreading codes for the data portion. The receiver operates in two stages: header detection and data detection. For header detection a conventional spread spectrum receiver is used. The headers are spread with a large enough processing gain to allow detection even in severe interference. A multiuser detector is used for the data portion to allow for decoding of overlapping active packets. It is shown that this system is detector capability limited and that it can significantly outperform conventional ALOHA systems whose performance is limited by the collision mechanism. This system also experiences a much smaller packet retransmission rate than conventional or spread ALOHA, and provides better spectral efficiencies.

Keywords: Multiuser Detection, Spread Spectrum, ALOHA, Random Access

1 Introduction

Packet broadcasting is a powerful strategy to share resources wherein a common channel simultaneously carries the communications of multiple uncoordinated users. Packet broadcast switching eliminates the need for routing and network switches. In such an environment, data from users are split into packets and transmitted in an uncoordinated fashion on a common transmission channel. Headers containing address and control information are added to the packet before transmission to identify ownership and assist in initial synchronization functions.

The ALOHA system developed at the University of Hawaii to connect geographically separated computer systems via a packet broadcasting network ushered in the era of modern random access communication systems, whose current use includes such popular communications technologies as the Ethernet. In a random multiaccess communication environment, users transmit information whenever they have something to send, independent of each other. Information may be lost because of collisions between packets from different users. Collision resolution strategies are needed to ensure reliable transmission of data, for example, unsuccessful packets are queued and a retransmission is attempted after a random delay. Throughput obtained with such a scheme, the original ALOHA system, is 18% of that of fully coordinated access to the

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channel, but allows for much simpler and more flexible receivers since no complex synchronization and user access data bases need to be maintained. The throughput of such random access systems can be improved to 36% by dividing time into slots and synchronizing users’ transmissions to these slots. Throughputs on the order of 48%–58% are obtained by using complex collision resolution protocols like tree algorithms, first-come-first-serve splitting algorithms and last-come-first-serve splitting algorithms. The improvement in throughput, however, is not significant when compared with the complexity involved in these algorithms [6].

Code Division Multiple Access (CDMA) [17] is a multiple access scheme where each user is assigned a unique identification sequence or spreading code. Knowledge of this code is necessary for detection at the receiver. CDMA enables multiple users to communicate simultaneously over the entire band of the spectrum, causing only limited interference among each other. CDMA forms the physical basis for our random access system. This is due to its popularity in current and future wireless networks such as the proposed wide-band CDMA systems [13]. In contrast to conventional CDMA systems, the proposed packet-switched system assigns a common access preamble to all users, which is spread by an identical spreading code. Multiple user separation for header access is facilitated by the asynchronous nature of the system, similar to Spread ALOHA [2, 1]. Spread spectrum technology is also one of the options for the IEEE 802.11 standard [8] defining a wireless standard for Local Area Networks.

A basic throughput analysis of random access CDMA is given in [10], where attainable throughputs are calculated if joint detection is used, and conclude that in a slotted system the average throughput approaches $K$, the capability of joint detection as $K$ becomes large. The system studied in [10] is packet-synchronized, and implicitly assumes that the receiver has knowledge of all accessing users and can detect the presence of any one of the users, which makes the receiver very complex for large numbers of joint users.

Conversely, [19] presents a study of an asynchronous system with an initial hand-shaking protocol, whereby users are tuned to the base station’s downlink paging channel and transmit their access preambles at a start time broadcasted by the base station. Results obtained in [19] state that the system capacity is limited by the acquisition method and is no larger than the capacity of slotted ALOHA, even with the use of joint detection.

In this paper we show that completely uncoordinated random access can achieve a throughput which approaches the capability of joint detection as [10] has shown for coordinated access. Furthermore, we present and motivate a practical signalling and accessing method which requires no knowledge of the accessing users at the receiver and works with a layered multiuser detector which requires receiver processing only for active packets.

The paper is organized as follows: In Section 2 we describe in detail the operation of the proposed system. In Section 3 we calculate the throughput of the proposed system and show that it can achieve full channel capacity in the limit of large joint detection capability. Packet retransmission rates, spectral efficiencies and throughput comparisons of the proposed system with the benchmark spread ALOHA are presented in Section 4.

## 2 System Description

The proposed packet random multiple access system supports a connectionless architecture where users do not need to maintain dedicated connections with the base station. A transmitted
packet of length $L_d$ consists of header and data frames as illustrated in Figure 1. The header frame of length $L_h$ consists of the access preamble and code identifier (ID). The access preambles of length $L_a$ are identical for all users using a fixed spreading sequence which acts as the access key to the system. The data portion of the packet is spread by a random spreading sequence, whose identification is contained in the code identifier (ID). The data portion of the packet is typically 2000–20000 bits long and hence the header constitutes a small overhead (see Figure 4).

In this paper, we assume that the transmitted signals are affected by Additive White Gaussian Noise (AWGN) with a one-sided power spectral density of $N_0$.

The receiver for the proposed system operates in two stages as indicated in Figure 2. The first stage deals with header detection, i.e., determination of the presence of a packet, accurate timing recovery, and decoding of the code ID. This information is used in the second stage of the receiver which deals with data detection.

The first stage of the receiver constantly monitors the channel for the presence of new active packets. If a new packet is detected, its timing is extracted, the code ID is decoded, and a new packet reception process is spawned off at stage II which is dedicated to the decoding of this packet. The stage II process performs packet specific despreading and matched filtering and passes this data to a multiuser detector which decodes concurrent packets jointly.

2.1 Stage I

2.1.1 Basic Operation

Stage I of the receiver deals with header detection and basic parameter extraction. Its front-end is an asynchronous filter matched to the chip pulse waveform, sampled at some adequate sampling rate. It next performs timing recovery according to an asynchronous digital method [4], which allows the receiver clock to be asynchronous to the transmitter clocks – an essential requirement for uncoordinated multiple access. Once timing is found, the code ID is decoded which contains packet information such as the particular random spreading sequence used in the data portion of the packet.

Detection of an active access preamble indicates the presence of a new active packet and, after symbol timing has been established, synchronization is performed by identifying a unique
Figure 2: Descriptive block diagram of receiver
sequence that indicates the end of the access preamble and the start of the code ID. An \( m \)-sequence can, for example, be used for this purpose. This synchronization information is supplied to the code ID decoder and the spreading sequence generator.

The frame synchronizer then triggers the code ID decoder. Each user chooses a random spreading sequence for each packet and transmits this information in the code ID portion of the packet which is error control encoded and is decoded using standard decoding techniques. This information is used by the spreading sequence generator to generate a symbol-synchronized, packet-specific spreading sequence for demodulation. The probability of multiple packets having the same code ID is small if a large code family is available.

Exact timing information, frame synchronization, and code ID information are passed on to Stage II, which is a software process dedicated to the detection of the packet. Stage I now becomes free again to search for new packet arrivals. It is tantamount for our system that Stage I is capable to detect new packets even in heavy interference, i.e., even if many packet transmissions are already in progress. This is ensured in the following way: Since the packet header forms only a small fraction of the entire packet, it is spread with a larger processing gain than the payload data. The active packets are spread by random sequences which constitute random interference which can be suppressed by the header processing gain to manageable levels, allowing header detection even in the presence of many active packets. Note that in the data detection stage increasing the processing gain is not possible without losing bandwidth, which is why a multiuser detector is necessary for Stage II.

2.1.2 Timing recovery

Timing acquisition in our random access scenario is synonymous with packet detection, since if the acquisition circuit detects a valid timing point, a header transmission is in progress. For this reason we discuss timing recovery in some more detail. A detailed discussion is beyond the scope of this paper, but the low SNR timing recovery algorithm assumed in our work has been thoroughly tested and patented [4].

The signal at the receiver front end during a received packet is

\[
y(t) = \sum_{j=1}^{J} x_j(t - \tau_j) + n(t) = x_J(t - \tau_J) + n(t) + I(t) \quad t \in [0, L_d T_h]
\]  

where \( J \) is the number of active users, \( L_d \) is the length of the packets in data symbols, \( \tau_j \) is the delay in arrival of the \( j^{th} \) packet and \( T_h \) is the symbol duration. It is assumed that \( 0 \leq \tau_j \leq L_d T_h \). The \( j^{th} \) transmitted packet is expressed as

\[
x_j(t) = \sum_{i=0}^{L_a-1} a_h(i) s_h(t - iT_h) + \sum_{i=L_a}^{L_h-1} a_c(i - L_a) s_h(t - iT_h) + \sum_{i=L_h}^{L_d-1} a_d(i - L_h) s_j(t - iT_b)
\]

where \( a_h(i) \) is the \( i^{th} \) symbol of the common access preamble and \( s_h(t) \) is the access preamble spreading sequence of duration \( T_h \) and is expressed as

\[
s_h(t) = \sum_{m=0}^{G-1} \beta_m g(t - m T_c)
\]
where $G$ is the *header* processing gain, i.e., the number of chips per symbol (whereas $N$ is the data processing gain), $T_c$ is the chip duration, $\beta_m \in \{-1/\sqrt{N}, 1/\sqrt{N}\}$ is the $m^{th}$ spreading chip of the access preamble and $g(t)$ is the unit-energy chip waveform. $G$ is chosen as an integer multiple of $N$ to facilitate the derivation of the data timing from the acquired header symbol timing. We are making our considerations with rectangular chip waveforms $g(t)$ for simplicity, but more bandwidth efficient pulse waveforms are state-of-the-art technology used in actual implementations [17]. The symbol $a_c(i)$ is the $i^{th}$ element of the block encoded code ID block. $a_d(i)$ is the $i^{th}$ bit of the data block and $s_j(t)$ is a random spreading sequence used in the data portion of the $j^{th}$ user. It has duration $T_b = (N/G)T_h$ and is expressed as

$$s_j(t) = \sum_{m=0}^{N-1} \alpha_{m,j} g(t - mT_c)$$

where $N$ is the processing gain of the data spreading sequence and $\alpha_{m,j} \in \{-1/\sqrt{N}, 1/\sqrt{N}\}$ is the $m^{th}$ spreading chip of user $j$.

The timing detector is concerned only with the access preamble, but must operate in strong interference $I(t)$. With this in mind, the matched filter receiver is given by

$$g_{MF}(T_h - t) = \sum_{m=0}^{G-1} \beta_m g(T_h + mT_c - t)$$

If $g(t)$ is a rectangular pulse, the sample matched filter $g_{MF}(mT_s)$ becomes particularly simple, where $T_s$ is the inverse of the receiver timing clock where we have used two samples per chip [4], i.e., $T_c/T_s = 2$, and $g_{MF}(mT_s) = \beta_{[m/2]}$.

The transmitter and receiver operate with asynchronous, independent timing clocks to allow completely uncoordinated access. However, clock accuracy on the order of 1ppm is expected to be obtained [7]. This means that the sampling clocks will drift no more than 1 sampling interval once every 1 million samples. Since typical packet sizes are about two orders of magnitude smaller, we can ignore transmitter/receiver clock frequency mismatches.

Using a suitable spreading sequence such as an $m$-sequence, the symbol-periodic outputs of both the in-phase and quadrature channels of the matched filter, $z(t)$ and $z(kT_s)$ (in the absence of noise), look approximately as sketched in Figure 3. The maximum likelihood estimate of the delay is given as [12],

$$\hat{\tau} = \arg \max_\tau E (|z(nT_b + \tau)|^2)$$

From $\hat{\tau}$, we calculate,

$$m_n = L_{\text{int}}(\hat{\tau}), \mu_n = \hat{\tau} - m_nT_s.$$  \hspace{1cm} (3)

where $m_n$ and $\mu_n$ are the integer part and fractional part of the delay $\hat{\tau}$.

The matched filter taps in the presence of noise and interference are given by,

$$z_k = z(kT_s) = \begin{cases} s(kT_s) + n_k; & \text{taps containing signal} \\ n_k; & \text{taps with no signal} \end{cases}$$
where $n_k$ is complex Gaussian noise and interference with variance $I_0/2$ in each dimension and $s(kT_s)$ is the signal at tap $k$, and is time and tap dependent as evident from Figure 3.

The digital timing recovery circuit [4] operates a time-varying interpolation filter which shifts the sample points such that they are symmetrically centered, shown by the solid dots in Figure 3. A dynamic analysis of this process is beyond the scope of this paper and we assume that the taps are aligned with the transmitter clock for a simplified feasibility analysis.

Since $z(kT_s)$ is Gaussian, $|z_k|^2$ is $\chi^2$ distributed [14]. Due to the triangular autocorrelation, which is a result of the spreading sequence, and with centered timing, i.e., $\tau = kT_s$, one of the squared taps will have signal value $E_s$, the adjacent taps have signal values $E_s/4$ and all other taps have signal value zero (see Figure 3), where $E_s$ is the symbol energy. Timing mismatch is measured in terms of $T_s$ and is calculated with reference to $\tau = 0$.

In a real system, the timing procedure needs to accumulate tap values to bring the signal level sufficiently above the noise floor to ensure accurate sample point detection. Peak detection of accumulated tap values is performed at the timing detector, noting that $(s^2(pT_s))$ is periodic with $N_{ts}$. Due to the lack of phase coherence at this point, for tap $p$, the algorithm calculates the accumulated tap energies

$$w_p = \sum_{j=0}^{L_a} |z_{k-jN_{ts}}|^2$$

(4)

where $N_{ts} = L_{\text{int}} \left( \frac{T_b}{T_s} \right)$, and $p = k \mod N_{ts}$. These tap values are $\chi$-square distributed [14] with $2L_a$ degrees of freedom, and $E[\omega_p] = L_a(E_s + I_0)(G/N)$ for the center tap, and $E[\omega_p] = L_a(G/N)I_0$ for the noise taps. Note that squaring of the tap values in (4) would not be necessary if the start of the packet was known and coherent signal addition could be performed. However, as packets are expected to arrive embedded in a lot of interference, the acquisition of the symbol clock time in the header is much less complex than accurate (optimal) determination of the packet start-time.

The sample point detection problem is now that of accurately identifying the sample point containing the largest signal component. Assume now that the timing mismatch is $\tau$ and we have the clock synchronized sampling, i.e., $\tau = kT_s$. This means that tap $w_\tau$ should be the maximum, i.e., $w_\tau > w_p$, $p \neq \tau$. Working with a frame of $M = 2G$ sample values and a detect
threshold $d_{th}$, the probability of correct detection is given by

$$P(\text{detect}) = P(\omega_\tau > d_{th}) \prod_{p=1}^{M} P(\omega_p < d_{th}) \prod_{i=-1,1} P(\omega_{\tau+i} < d_{th})$$

On the other hand, the probability that either a noise sample is mistakenly identified as a valid timing point, or one of the samples adjacent to the maximum sample, is given by

$$P(\text{false}) = 1 - P(\omega_{\tau+1} < d_{th})^2 P(\omega_\kappa < d_{th})^M$$

Note that this is also an upper bound on the probability a timing recovery detect is signalled when there is no packet header transmission in progress.

These probabilities can be calculated in a straightforward way by noting that all the $w_p$ are $\chi$-square distributed, with cumulative probability density functions

$$F_W^{(c)}(w) = 1 - e^{-w/I_0} \sum_{k=0}^{2L_a-1} \frac{1}{k!} \left( \frac{w}{I_0} \right)^k$$

noise taps

$$F_W^{(n)}(w) = 1 - Q_{L_a} \left( \sqrt{\frac{L_aE_sG/N}{I_0/2}}, \sqrt{\frac{w}{I_0/2}} \right)$$

signal taps

where $Q_m(w/\sigma, \sqrt{w}/\sigma)$ is the generalized Marcum’s $Q$ function [14].

The length of the access preamble depends on the number of symbols needed to obtain a high probability of correctly identifying the timing point with a low probability of false alarms. Figure 4 shows the probability $[F_W^{(c)}(w)]^M$ that all noise taps are smaller than $w$, as well as the probability $F_W^{(n)}(w)$ that the center tap is smaller than $w$, for $G_{E_a}/(NI_0) = 3\text{dB}$, a header length of $L_a = 50$, and $M = 64$. The value of $3\text{dB}$ corresponds to a CDMA system where the number of active packets is equal to half the (header) processing gain $G \geq N$ of the system. As can be seen, a threshold of $w = 80$ will produce header detection error rate $\approx 0$, since all noise taps are smaller than $w = 80$, and the probability that the center tap is smaller $w = 80$ is less than $10^{-5}$. This is meant to demonstrate that accurate header detection is feasible even in a high interference environment with a header size no more than about 1% of a typical packet size. Of course, in a practical system the detection thresholds as well as the header length need to be determined carefully given all the system parameters.

2.1.3 Stage II

The second stage of the receiver employs joint detection of the transmitted data. The input to this stage consists of timing information, frame synchronization information and the code ID which determines the spreading sequences used for all the active packets. Joint detection methods [11, 18, 15, 3, 16] such as interference cancellation, decorrelation, projection receivers or more sophisticated turbo iterative decoding strategies can be used in the second stage of the receiver. However, for ease of a flexible implementation, we envision the use of iterative decoders where additional users can easily be added or dropped corresponding to the rapidly varying numbers of jointly active packets.
Figure 4: Cumulative probability density of the center tap and $M$ noise taps, for $M = 64$, $L_a = 50$, and $GE_s/(NI_0) = 3$dB, illustrating that $d_{th}$ would provide reliable header detection.

The basic structure of such iterative multiuser detectors [3, 16] is shown in Figure 5, and consists of a simple interference suppression stage and a bank of parallel single channel decoders. The interference suppression stage is the only part of the receiver which needs to be laid out for the maximum number of users. In the systems studied in [3, 16] this stage is a simple interference cancellation process where interfering signals are subtracted from the received signal. The single user decoders can be software processes which can be spawned off as required. Such iterative receivers have been studied fairly well, and the performance results of the receivers presented in [16] will be used later in this paper to obtain spectral efficiency figures.

3 System Throughput

In this section, we calculate the system throughput, defined as the total number of successful accesses to the system. All calculations are normalized to the header length $L_h$, which is constant for all users, and, as we will see, is an important system constant.

Such system throughputs have been calculated for a packet-synchronized slotted system as envisioned in future wide-band CDMA applications by Liu et. al. [10], who found that in the limit of large joint detection capability, denoted by $K$, the system throughput asymptotically approaches $K$.

In our system, initial packet transmission failure can occur in two ways: failure in detecting the header or failure in joint detection. Hence, successful transmission is defined as successful header detection and successful joint detection. Let $P_p$ denote the probability of packet survival, $P_h$ denote the probability of successful header detection and $P_m$ denote the probability of successful joint detection. Hence,

$$P_p = P_h P_m$$

Header access is similar to a pure ALOHA system. Each packet needs a traffic-free interval
of $2L_h$ for successful transmission of the header. Note that this represents an upper bound and is inspired by our assumption that there is only one header detection circuit operating at the receiver. Due to the spreading, even overlapping headers can be detected similar to the spread ALOHA mechanism [1], reducing the vulnerability time. However, as we will see, header collisions do not represent the ultimate system limitation.

Assuming a Poisson arrival of packets at rate $\lambda$ packets/header length,

$$P_h = e^{-2\lambda}$$

For successful joint detection, the total interfering traffic should be less than the capability of the joint detector. Assuming a detector capable of detecting $K$ users, we require that there are no more than $K$ active packets in a time span $2L_d$ of two packets, and

$$P_m = P(J \leq K - 1 | \text{during } 2L_d)$$

According to the Poisson process,

$$P(J = k) = e^{-2\lambda \frac{L_d}{L_h}} \frac{(2\lambda \frac{L_d}{L_h})^k}{k!}$$

Using (3) and (6), we obtain

$$P_m = \sum_{k=0}^{K-1} e^{-2\lambda \frac{L_d}{L_h}} \frac{(2\lambda \frac{L_d}{L_h})^k}{k!} = f\left(K, 2\lambda \frac{L_d}{L_h}\right)$$
The function \( f(K, \nu) \) converges to the step function \( S(\frac{\nu}{K}) \) as \( K \rightarrow \infty \) [10], where

\[
S(x) = \begin{cases} 
1 & \text{if } x < 1, \\
0.5 & \text{if } x = 1, \\
0 & \text{if } x > 1 
\end{cases}
\]

This shows that in the limit the multiuser detector always provides successful detection as long as the arrival rate \( \lambda < \frac{(L_h/L_d)/(K/2)}{K/2} \), i.e., the average arrival rate per packet is not larger than \( K/2 \). This is a consequence of the law of large numbers, and it is important to note that this holds in the limit. Comparisons with realistic values of \( K \) are shown in Figures 6 and 7 below. Note that for a slotted system the capacity can be twice as large [10], just as with classical ALOHA.

The Poisson distribution in (7) asymptotically converges to a Gaussian distribution [9] with mean and variance \( 2\lambda \frac{L_d}{L_h} \). Hence,

\[
P_m \xrightarrow{\frac{L_d}{L_h} \rightarrow \infty} \int_0^{K-1} \frac{1}{\sqrt{4\pi \lambda \frac{L_d}{L_h}}} \exp \left( -\frac{\left( x - 2\lambda \frac{L_d}{L_h} \right)^2}{4\lambda \frac{L_d}{L_h}} \right) dx \\
\approx 1 - Q \left( \frac{K - 1 - 2\lambda \frac{L_d}{L_h}}{\sqrt{2\lambda \frac{L_d}{L_h}}} \right) \tag{8}
\]

Using (5), the probability of packet success \( P_p \) can now be represented as

\[
P_p = e^{-2\lambda} \left( 1 - Q \left( \frac{K - 1 - 2\lambda \frac{L_d}{L_h}}{\sqrt{2\lambda \frac{L_d}{L_h}}} \right) \right) \tag{9}
\]

and the system throughput is

\[
R = \lambda \frac{L_d}{L_h} e^{-2\lambda} \left( 1 - Q \left( \frac{K - 1 - 2\lambda \frac{L_d}{L_h}}{\sqrt{2\lambda \frac{L_d}{L_h}}} \right) \right) \quad \text{[packets/packet duration]} \tag{10}
\]

In Figure 6, system throughput, which is normalized to the packet size \( L_d \), is plotted against the arrival rate \( 2\lambda \frac{L_d}{L_h} \) in packets/packet duration for the case of a joint detector with capability \( K = 10 \) (see (7)). Figure 6 also illustrates the effect of packet size on system throughput and the limitations on system throughput imposed by the multiuser detector and header collisions. Note that for \( \frac{L_d}{L_h} > 100 \), throughput is limited by the multiuser detector capability according to (10) and header collisions become negligible.

Figure 7 shows the same plot with a multiuser detection capability of \( K = 50 \). It becomes evident that the limiting throughput \( \rightarrow K/2 \) quite slowly, reaching 72% for \( K = 50 \), that is, the large detector capability limit calculated in [10] is quite challenging to approach with realistic values of the joint detection capability.
Figure 6: Throughput for varying packet sizes for a multiuser detection capability of $K = 10$.

Figure 7: Throughput for varying packet sizes for a multiuser detection capability of $K = 50$. 
4 Channel access via CDMA

We now return to the question of physical channel access, which in our system is accomplished via CDMA as discussed in Section 2. This is the same accessing method used in spread ALOHA [1], which we use as a benchmark for packet retransmission rates, i.e., the probability of transmission failure at any particular attempt, throughput and spectral efficiency. Spread ALOHA uses a bandwidth greater than the signal bandwidth by the spreading factor $N$. The ALOHA channel signals are modified by spreading each bit in time, with all users employing the same spreading sequence. The ordinary ALOHA contention protocol is used to control access. At the receiver, the asynchronous timing of the packets means that unless packets collide within a chip time, concurrent transmissions are suppressed by the processing gain and can be successfully decoded. Nonetheless, it turns out that the throughput is identical to the classic ALOHA system. The main difference, apart from the random spreading sequences used, between spread ALOHA and the proposed scheme, is that the new system is detector performance limited whereas the Spread ALOHA system is collision limited.

Spread ALOHA can in fact be seen in terms of the concepts developed here in the following way. Spread ALOHA is equivalent to having a collision vulnerable zone, $L_h$, which is the total packet length $L_d$ divided by the processing gain $N$, $L_h = L_d/N$. Furthermore, spread ALOHA does, strictly speaking, perform concurrent (joint) detection, where the interfering packets, suppressed by the processing gain of the spread spectrum system, are treated as noise. As seen later, this fixed packet length to header ratio $L_d/L_h$, and the limited capability of receiver is what limits the performance of spread ALOHA compared with the proposed accessing scheme.

Differences also result in the retransmission performance. Figure 8 shows the probability of packet retransmission for various detector capabilities of the proposed system and spread ALOHA. For the proposed system operating at the optimal traffic rate for spread ALOHA and with $K = 20$, the probability of packet retransmission is 10% as compared to 60% in spread ALOHA. This reduced packet retransmission rate results in smaller buffer sizes in the proposed system, offsetting some of the complexity of the receiver.

In Figure 9, the throughput of the proposed system and spread ALOHA are plotted against the arrival rate $\lambda L_d/L_h$ in packets/packet duration. Depending on how much interference spread ALOHA can tolerate, the throughput changes according to formulas analogous to those derived in Section 3. Values for three cases are plotted: $K = N/2, N$, and $K = 2N$, for three values of the interference tolerance for spread ALOHA ($N/5, N/2, N$). The proposed system can achieve significantly higher throughputs given good joint detector capability, with maximum throughput values close to the arrival rate.

Figure 9 also compares spectral efficiencies of the proposed system with spread ALOHA, shown by the axis on the right hand side. In order to achieve the high level of joint detection considered, we assume that an iterative multiuser detector [16] using a rate $R = 1/3$ error control code is employed, resulting in the required $E_b/N_0$ values indicated in the figure. For comparison we also assumed that spread ALOHA employs a turbo code of approximately equal complexity. Since spread ALOHA does not employ joint detection, a required $[E_b/I_0]_{req} = 0.8$dB for the turbo code considered [5] translates to an actual $E_b/N_0 = 1.55$dB $E_b/N_0 = 3.0$dB for $K = N/2$, $E_b/N_0 = 7.8$dB for $K = N$, and values larger than $K = 1.247N$ cannot be supported anymore since the required $[E_b/I_0]_{req}$ for the turbo code is no longer attainable.

The signal-to-noise ratio is calculated from the required signal-to-interference ratio as fol-
Figure 8: Probability of packet retransmission

Figure 9: Throughput comparison with Spread ALOHA
lows:

\[
\frac{E_b}{I_0}_{\text{req.}} = \frac{E_b}{2 \left( \text{noise variance} + \text{multiuser interference} \right)}
= \frac{E_b}{2 \left( \frac{N_0}{2} + \frac{K}{N} E_s \right)}
\] (11)

Hence, from (11), the actual $E_b/N_0$ needed is

\[
\frac{E_b}{N_0} = \frac{\left[ \frac{E_b}{I_0} \right]_{\text{req.}}}{1 - \frac{2RK}{N} \left[ \frac{E_b}{I_0} \right]_{\text{req.}}}
\] (12)

In the light of this discourse and Figure 9 it becomes evident how spread ALOHA is collision limited, whereas the proposed system can increase its throughput as more resources become available in the form of signal-to-noise ratio, and/or detector capability.

5 Conclusion

A new packet-based, random multiple access method is proposed, analyzed, and compared with Spread ALOHA. It is shown that the proposed system offers higher throughput, higher spectral efficiencies, lower retransmission rates and smaller buffer sizes compared to Spread ALOHA, making use of a unique packet format and joint detection capabilities at the receiver. It is shown that the proposed system can achieve a throughput which approaches the maximum possible as the joint detector capability becomes large. A comparison of the spectral efficiencies of the proposed system with spread ALOHA and required $E_b/N_0$ assuming an iterative turbo decoding scheme shows that the spectral efficiency of the proposed system can be several times higher than that of Spread ALOHA. The proposed system is detector capability limited, rather than collision limited as Spread ALOHA. This has been accomplished with a novel packet format which relies on spreading processing gains to detect packets, and on joint detection capabilities to receive and decode concurrent packets.

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