A Dynamic Adaptive Multi-receiver Random Access Protocol for the Code Division Multiple Access Channel

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Abstract

In this paper we present a packet multiple access protocol that is a hybrid of a pure CDMA protocol and an ALOHA random access protocol. The protocol utilizes the multi-reception capabilities of spread-spectrum communications together with the "statistical-multiplexing" capabilities of random access. We begin by presenting a multi-receiver random access protocol and analyze its throughput characteristics. We then develop collision resolution algorithms for the protocol that attempt to optimize its performance. These algorithms are analyzed through the use of simulation. We show that with proper choice of protocol parameters our protocol can handle all admissible traffic loads. We then propose a dynamic, adaptive extension to the protocol that uses limited feedback information to allow the protocol to vary its parameters based on the traffic load in the system. This dynamic, adaptive version of the protocol allows it to operate efficiently under a wide variety of traffic load conditions. At very light load conditions the protocol behaves as a pure random access protocol and at very high load it behaves as a pure fixed assignments protocol. Our protocol seems to be a good choice for providing random access on a satellite channel where propagation delays are long. It is also a natural choice for wireless transmission of very short (e.g., ATM) packets.

I. Introduction

Most work on packet multiple access protocols concentrates on either fixed assignments or random access. With fixed assignments multiple access the channel is divided into a number of independent sub-channels and each user is assigned its own sub-channel, in a static fashion independent of its activity. With random access all users share a single channel using some form of contention. While fixed assignment schemes are particularly efficient in handling steady continuous traffic, they are inefficient for bursty traffic. Conversely, random access schemes are more efficient for bursty traffic but are not as efficient for continuous traffic. This gives rise to the classic integration problem where one needs to design a multiple access protocol that can efficiently handle both bursty and continuous traffic. Most work on multiple access protocols has treated this integration problem separately[1]. That is, a separate sub-channel was allocated for random bursty traffic, while the rest of the channel was allocated to continuous stream traffic, in effect avoiding the integration problem all together.

In this paper we do not attempt to design another integrated services multiple access protocol. Instead we develop a protocol that dynamically alters its behavior based on the traffic load in the system. Under low traffic loads our protocol operates in a pure random access mode. As the traffic load increases our protocol gradually changes toward a fixed assignment system. We show that this protocol is capable of efficiently handling a wide variety of traffic loads. Our protocol is designed to operate in the Spread Spectrum radio environment. While in this paper we restrict our discussion to spread spectrum radio, simple extensions to other environments can be made and are discussed in the conclusion.

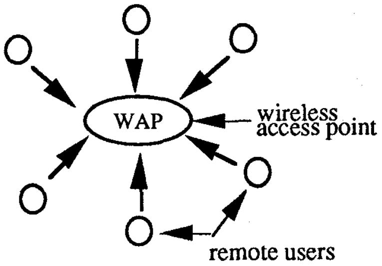

Figure 1. Network topology.

The network under consideration is shown in figure 1. It consists of a large number of wireless users communicating with a central wireless access point (WAP). The users are assumed to be communicating with the wireless access point using spread spectrum radio. In the past, the use of spread spectrum was dictated by the need for secure military communications. In recent years, however, spread spectrum has become a popular signaling approach for commercial applications as well. Spread spectrum provides a simple and effective way to combat multipath interference, and is also a simple and natural way to provide multiple access to the medium. In addition, recent regulation on the use of the Industrial Scientific and Medical (ISM) frequency bands requires the use of spread spectrum signaling. Last, and possibly most important, spread spectrum Code Division Multiple Access (CDMA) has been shown capable of

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providing greater frequency reuse capabilities when operating in a cellular environment[2].

In our proposed system, multiple access is provided using a version of Code Division Multiple Access (CDMA). In theory, if the different users are assigned orthogonal CDMA codes, they can be kept orthogonal, and thus CDMA is equivalent to Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA). However, even when orthogonal CDMA codes are employed, orthogonality is very difficult to maintain in a practical PN system due to timing uncertainties. Additionally, when operating in a multi-path environment, multiple path receptions from different users can not be kept orthogonal from one another. Therefore, it is common in practice to use quasi-orthogonal CDMA sequences that are not orthogonal to one another but instead have low cross correlation properties. This results in secondary interference between the users. That is, the lack of orthogonality between the users may result in transmission errors, the rate of which is a function of the number of non-orthogonal users simultaneously occupying the channel.

In general, for a given performance level (transmission rate and error probability) the number of users that can simultaneously use the channel in a CDMA system is dependent on the modulation/coding scheme employed, the propagation properties of the medium, and the receiver implementation. These issues have been studied extensively in the literature and will not be addressed in this paper. It has been shown that when using Direct Sequence CDMA, the interference from other users can be approximately modeled as additive white Gaussian noise[2]. With this assumption, when the number of users is large, we can express R_M, the achievable transmission rate of each user (ignoring thermal noise at the receiver), as

$$\mathrm{R_M} = \frac{\mathrm{W}}{\mathrm{M} \times (E_b / N_0)_{\mathrm{req}}} \tag{1}$$

Where M is the number of users that are simultaneously transmitting, W is the system bandwidth and $(E_b / N_0)_{req}$ is the required bit energy to noise ratio for the modulation/coding scheme employed that results in acceptable performance. Of course, equation (1) assumes that the users are exercising perfect power control in order to provide equal power levels from each user at the WAP. Also, equation (1) holds for a large number of users, when the number of users is small higher transmission rates may be achievable. We use this model to give an approximation for the transmission rate in a CDMA system. For simplicity, we now assume that when M users communicate at rate R_M each, their packets arrive error free at the receiver. However, if more than M users attempt transmission simultaneously at rate R_M, all of their packets will contain errors and require retransmission. This assumption is idealistic. In practice, even when fewer than M users attempt transmission errors may occur, and similarly, when more than M users attempt transmission some packets may still get through error-free.

A system can now be designed to allow each user his own CDMA code and signal at a rate that would provide acceptable error performance. Such a system would essentially be equivalent to an orthogonal multiple access system such as fixed TDMA or FDMA, and may be an appropriate approach for applications requiring a continuos stream of constant bit rate traffic (such as digitized voice or a very long file transfer). For random packet traffic, however, a fixed assignment scheme is clearly inefficient. It is well known that such traffic is much more efficiently handled by random access protocols such as ALOHA and CSMA; these protocols allow a large number of low traffic rate users to share a single channel in a contention mode[3].

Most spread spectrum systems provide multiple access in one of two ways; providing each user a different CDMA code, and having no contention; or, having all users share a single spreading code and achieve multiple access through some form of contention. The latter has the disadvantage of being spectrally inefficient due to band spreading and the former, while more spectrally efficient due to the CDMA, is inefficient in handling random packet traffic. In this paper we consider an alternative system that provides multiple access using both CDMA and contention.

II. The System Model

Consider a system with N users. Each user communicates with the WAP using a different CDMA spreading code at a transmission rate R_M. The receiver at the WAP attempts to receive the transmission of each of the N users, and is capable of doing so as long as the number of users transmitting simultaneously does not exceed M. When more than M users transmit simultaneously a collision occurs and all of the transmissions fail.

If each of the users was transmitting a continuos stream of traffic, then the system could only support a total of M users (i.e., N=M). However, since our users are transmitting random packet traffic, there is the potential of supporting a much larger number of users.

This is the random access aspect of the protocol. Our CDMA system is designed for M simultaneous users and since users are not always transmitting, a larger number of users can be supported. We assume that the users have fixed length packets arriving according to a Poisson random process. We begin by noting that the aggregate signaling rate over the channel when exactly M users transmit is R=MR_M. We assume, for simplicity of the presentation, that packets are of unit duration on the aggregate channel. That is, they are of duration M units when transmitting at rate R_M. Packets arrive at each user, for transmission over the channel, according to a Poisson random process of rate λ packets per time unit (resulting in a total arrival rate in the system is λN packets per time unit). Therefore, the probability of a user having n packet arrivals in a time unit is,

$$P(n) = \frac{\lambda^n e^{-\lambda}}{n!}. \tag{2}$$

III. The Random Access Protocol

We develop a natural extension of the Slotted Aloha protocol to this multi-receiver channel model. We divide the time scale into slots of one packet duration. Since a packet takes M time units to be transmitted, a slot is equal to M time units. We assume that the users' are slot synchronized. That is, synchronization is maintained in the system so that all users' slots begin and end at the same time. When a new packet arrives at a node it is immediately transmitted at the beginning of the next slot. We assume that if more than M users attempt transmission during the same slot a collision occurs and none of the packets are received correctly, otherwise all of the packets are correctly received. Upon a collision all of the colliding packets must be scheduled for retransmission at a later time. The actual performance of this multi-receiver random access protocol greatly depends on how collisions are resolved in the system. However, considerable insight can be gained into the algorithm by first analyzing its throughput performance. A crude, but insightful, approximation is that colliding packets are retransmitted at a much later point in time and therefore they do not affect the traffic load in the slots immediately following a collision but only affect the overall packet transmission rate. This approximation essentially says that the load on the channel is independent from slot to slot. Though such an approximation is grossly inaccurate in predicting delays, it turns out to give a good estimate of the throughput performance when random collision resolution is employed and is widely used in the analysis of random access schemes[4].

Let the probability a user has a packet to send during a given slot be p. Using the assumption discussed above this probability represents both new packet arrivals as well as re-transmissions of old packets and is independent from slot to slot and between users. Now, the number of transmission attempts during a given slot is Binomially distributed. The probability of i transmission attempts is expressed by,

$$P(n=i) = \binom{N}{i} p^i (1-p)^{N-i}, \tag{3}$$

where N is the number of users in the system. The probability of a collision is the probability that n>M and is equal to,

$$P(collision) = \sum_{i=M+1}^{i=N} \binom{N}{i} p^i (1-p)^{N-i} \tag{4}$$

and the throughput, T, is the average number of successful packets and is expressed by,

$$T = \frac{1}{M} \sum_{i=1}^{i=M} i \times \binom{N}{i} p^i (1-p)^{N-i} \tag{5}$$

where the 1/M factor normalizes the throughputs to the number of available traffic streams (M). Figure 2 shows throughput vs. p for a system with 10 users (N=10). The maximum obtainable throughput, for a given M, is the peak point on the curve. When M is equal to 1 we have ordinary slotted ALOHA with throughputs of about 0.37. When M=10 we obtain, essentially, the fixed assignment algorithm with throughput of 1. The throughputs gradually increase with M so that in effect we go from full contention with M=1 to pure fixed assignments with M=10.

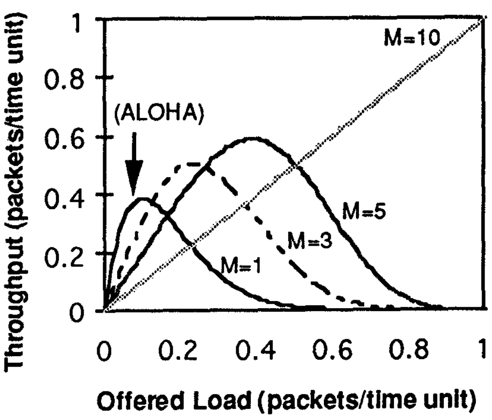

Figure 2. Throughput vs. Offered Load

These results tell us that higher throughputs are achievable with larger values of M. For example, when we have a large number of users we can increase the throughput of the system to 0.6 by using M=10 (that is by designing the system to allow 10 users to communicate simultaneously). Having M=10 in a system of 100's or 1000's of users is a very reasonable system and results in significant throughput improvement. Throughput, however, is just one measure of performance in a random access scheme. Another very important measure is packet delay. The delay performance of the algorithm, of course, depends on how collisions are resolved which is the subject of the next section.

IV. Collision Resolution

There has been substantial amount of work done on collision resolution algorithms for ordinary slotted ALOHA. Unfortunately, most of these results do not directly apply to this multi-receiver random access protocol, because they greatly depend on the fact that collisions typically involve two packets (in ordinary ALOHA if two nodes attempt transmission a collision occurs).

A simple collision resolution protocol would allow nodes to attempt retransmission after a collision in the subsequent slots with a fixed probability *p*, until the transmission is successful. Clearly, the performance of the algorithm depends on the choice of *p*. In [5] an algorithm is described that selects a value of p based on estimates of the traffic load in the system. Figure 3 shows the delay achieved using this protocol for various values of M. As can be seen from the figure when the arrival rate is low the value of M that results in the minimum delay is 1. As the arrival rate increases, so do the number of collisions, and at some point a value of M=5 results in better performance. When the arrival rate becomes sufficiently large the best performance is obtained with a value of M that is equal to N where each node essentially has a dedicated channel and no contention occurs. That is, for very high arrival rates, the best performance is obtained with a fixed assignment scheme.

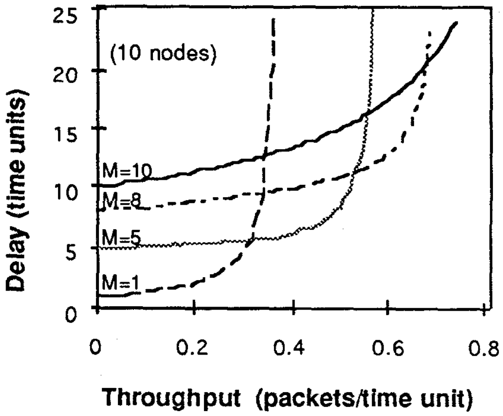

Figure 3. Delay vs. Throughput for 10 user system.

V. Adaptive Algorithm for Varying M

Since the performance of multi-receiver Aloha depends on the traffic load, a natural extension to the protocol would be to allow M to vary with the traffic load. One way to do this is for the WAP to make an estimate of the traffic load (using the collision statistics) and vary the value of M based on that estimate. As the WAP changes the value of M, it broadcasts it to the users so that they can alter their transmission rates for the value of M (transmission rate = R/M). Such an extension would provide a natural, smooth transition from full random multiple access to fixed assignment multiple access that is based on the traffic load in the system. Values of M that are between 1 and N represent a system that is neither pure random access nor fixed assignment. The performance of this adaptive system would be as good as the performance of the random access protocol with the optimal value for M for every value of the load in the system.

An even more ambitious system would require the WAP to determine the number of users involved in a collision during every slot and alter the transmission rate on a slot by slot basis. If it were possible for the WAP to determine the exact number of users involved in a collision then an algorithm can be designed that achieves near optimal performance. The WAP broadcasts its estimate of the number of collisions in a slot (M'). In the next slot, only those users involved in the collision are allowed to transmit. They all re-transmit their packets at a transmission rate R/M', so that no collisions occur and all of the transmissions are successful. In the next slot, the system returns to normal operation where all of the users are allowed to transmit.

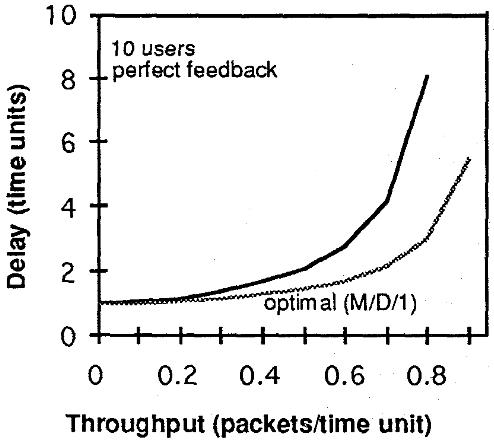

Figure 4. Multi-receiver ALOHA with feedback.

As an example, we consider a system with M=1 where all users transmit at rate R. A collision occurs if more than one users attempt transmission at the same time. When a collision occurs, the WAP broadcasts the size of the collision set (M') and in the next slot only those users involved in the collision transmit at a rate R/M'. Following that transmission, all users return to ordinary operation with M=1 and transmission at rate R. We plot the performance of this system (obtained via simulation) in Figure 4. As can be seen from the figure, this system performs better than any of the previously considered collision resolution algorithms. It is interesting to compare the performance of this system to that of an optimal (centrally controlled) scheduling system. As can be seen from Figure 4, for low arrival rates this system behaves almost optimally.

VI. Conclusion

The protocol presented in this paper is a hybrid between a pure random access protocol and a fixed assignment protocol. It was developed to operate in the spread spectrum environment, although extensions can be made to other environments. For example, instead of using CDMA one can use TDMA or FDMA to provide the multiple orthogonal traffic streams. Then, users can access these streams by choosing a stream at random for the transmission of each packet. Of course, such a system would not behave as nicely as the CDMA system because collisions may occur even when just two users attempt transmission if they both choose the same stream. However, a TDMA or FDMA system has the advantage of being completely orthogonal and therefore capable of accommodating more users. The analysis of such a system would be very similar to that presented in this paper and should yield similar results.

The system that we discussed assumes the presence of a matched filter receiver (with a unique PN sequence) for each user, for systems with very large number of users this may be too costly. Again the system can be slightly altered to allow a number of users to share a PN sequence. In this case the system's performance will not be as good because collisions may take place where two or more users attempt transmission with the same PN sequence.

The multi-receiver random access protocol presented in this paper offers higher throughput capabilities than the ALOHA protocol. However, it is not necessarily more efficient than Carrier Sensing Multiple Access (CSMA) protocols. Our protocol can be a logical choice in circumstances where Carrier Sensing protocols (or similar variations such as busy tone multiple access) would not be efficient. For example, CSMA can not be used on the satellite channel where propagation delays are high. Also, recently much has been said about wireless transmission of Asynchronous Transfer Mode (ATM) packets. Since ATM packets are only 53 bytes long, using CSMA, again, may be very inefficient and our multi-receiver random access protocol may provide a logical alternative.

Finally, in our discussion of collision resolution protocols we consider random collision resolution where each node attempts to retransmit its packet independently of other nodes. It has been shown that in circumstances where nodes are able to obtain immediate feedback about the transmissions of other nodes, collision resolution can be improved by using tree splitting algorithms[4]. These algorithms have been developed for the pure ALOHA protocol, and their extension to the multi-receiver random access protocol is not obvious; however, it seems like they would be a natural choice for the multi-receiver protocol and should further improve its performance.

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