PAPER

The Coded Tone Sense Protocol for Multihop Spread Spectrum Packet Radio Networks

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SUMMARY In Spread Spectrum Packet Radio Networks (SS/PRNs), different spreading codes are required for different stations for transmitting packets. Therefore multihop SS/PRNs with a large number of stations would require a large number of codes and hence a large channel bandwidth. In this paper we design a code assignment algorithm which could reduce the number of codes required to about 22%. Further reducing the number of codes is found to cause little throughput degradation. The Coded Tone Sense protocol is designed for using these codes in multihop PRNs. Simulation result shows that in a 80 node network using only 5 spreading codes, the maximum network throughput is about 73% higher than the BTMA protocol.

key words: *communication protocol, packet radio networks*

1. Introduction

Since the evolution of the ALOHA system [1], Packet Radio Networks (PRNs) have become an attractive field of research. As the network size gets larger, a distributed multihop network is needed to connect all stations. It is well known that the CSMA protocols can give a higher throughput than the ALOHA protocol in a centrallized PRN. But its performance degrades in a multihop network environment [2]-[3]. This is mainly due to the hidden station problem which could be solved by the use of a busy tone [4]. All the above protocols are primarily designed for use with conventional radio signals. If there is overlap of transmissions from different stations, all the packets involved would be destroyed.

In spread spectrum techniques, the radio signal is encoded using pseudorandom sequences. The spreading sequences permit the receivers to distinguish one spread-spectrum transmission from another and form a Code Division Multiple Access (CDMA) system. The use of a CDMA protocol allows overlapping of transmissions by assigning a different code to each transmitted signal. The characteristics of spread spectrum influence the choice of channel access protocols in PRNs [5].

In [6] Brazio and Tobagi presented a model for the throughput analysis of multihop spread spectrum PRNs. The access protocols considered include nonpersistent CSMA, pure ALOHA, conservative BTMA and Destination Code Sensing Multiple Access (DCSMA). Numerical results are only shown for some simple topologies with 3 to 4 nodes. In DCSMA, the source station monitors the channel for the transmission using the destination code of its packet prior to the transmission of its packet. This protocol is the same as the Receiver-base CSMA protocol [7] where the CSMA protocol is embedded on a single hop spread-spectrum PRN with an unique spreading code allocated to each station for receiving packets.

Chen and Boorstyn [8] presented an approximate throughput analysis of a CDMA protocol in multihop PRNs. The effect of connectivity on network throughput in the presence of noise is also investigated. In [9], the study was extended to include BTMA and PSMA (Preamble Sense Multiple Access). In PSMA, a station will receive a packet from a negihbour, whether addressed to it or not, only if the initial portion (preamble) of the packet is not interfered. A level of noise immuniuty for the CDMA protocol is defined. Thus in CDMA/n, an idle station can successfully receive a new packet if there are less than n transmissions in its neighborhood. It was concluded that for random networks and uniform end-to-end traffic, the protocols can be ranked in order of perfomance as CDMA/∞, $\cdots$, CDMA/2, BTMA, CSMA, PSMA and CDMA/1 (ALOHA).

In [10] Birk and Tobagi proposed to equip a station that has a very high inbound traffic with multiple receivers. Several possible architectures and code assignment policies were proposed and compared for such stations using the pure ALOHA access scheme.

In multihop PRN, a large number of stations requires a large number of spreading codes and hence a larger channel bandwidth. Moreover as CSMA performance degrades in a multihop environment, a more suitable protocol is needed to make good use of spread-spectrum techniques. Since the spreading codes assigned to the stations need to be unique only to its neighbours, the codes could be reused by stations which are farther apart. In this paper, we first propose

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Manuscript received September 8, 1992.

Manuscript revised March 8, 1993.

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a code assignment algorithm based on the code reuse property. A new protocol termed Coded Tone Sense (CTS) is introduced in Sect. 3. Code assignment examples and simulation results are presented in Sect. 4.

2. System Model and Code Assignment Algorithm

Let there be N stations in a packet radio network and let their locations be fixed. Each station is assigned a code and a station-number. The station-number is globally unique, but the code is unique only in each station's neighbourhood. Let the transmission range be R for all stations. Each station has only one receiver and one transmitter and all stations use the same frequency band for transmitting packets. Stations therefore cannot transmit and receive data packets at the same time.

Each station is assigned a code for identifying itself from its neighbours. Since the codes are local in nature, beyond a certain range, which we call it the local-range for convenience, they can be reused. The size of the local-range depends on R and the distribution of neighbouring stations. The local-range of a particular station is formed by the perimeters of the transmission ranges of the station's neighbours (Fig. 1). Each station is first assigned a code to distinguish itself from the other stations within its local-range. The algorithm for assigning codes to stations is as follows:

(1) $m:=1$.
(2) Select an unassigned station and denote it as S_0.
(3) Assign code m to S_0.
(4) $S:=S_0$.
(5) Mark all the stations in the local-range of station S.
(6) If all unassigned stations are marked, go to (9).
(7) Assign code m to one of the unmarked stations S'.
(8) $S:=S'$; go to (5).
(9) If all stations are assigned, stop. Otherwise unmark all unassignd stations.
(10) $m:=m+1$; go to (2).

We denote the total number of codes required using the above algorithm as K_1 and the initial code assigned to station j as code A_j which is an integer between 1 and K_1. Note that K_1 codes are needed to avoid code collisions. But in PRNs, collision of packets due to time conflict is common. Therefore, if code collision can be tolerated, the total number of codes K_1 can be reduced to save bandwidth. We shall show in Sect. 4 that when the number of codes is reduced to a small fraction of K_1 only a small throughput degradation is observed. The criteria of sharing codes depends on the station distribution and the traffic on the network. Here we choose, for simplicity, to allocate codes so that the number of stations sharing a code is as even as possible. Let $K_2(\leqq K_1)$ be the desired number of codes and code C_j be the final code assigned to station j. Then

$$C_j=\begin{cases} K_2 & \text{if } A_j \text{ mode } K_2=0 \\ A_j \bmod K_2 & \text{otherwise.} \end{cases}$$

For example, consider a case where initially a total 30 (K_1) codes is required to avoid code collision. Suppose code 14 is initially assigned to station 5. When the desired number of final codes (K_2) is 10, then the final code assigned to station 5 is code 4.

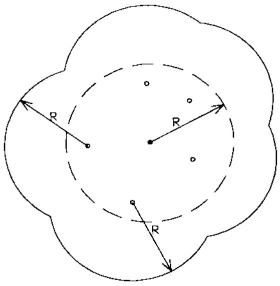

Fig. 1 The local range.

3. The Coded Tone Sense Protocol

To avoid being interfered by the neighbouring stations, a station will broadcast a busy tone during its packet reception. The receiving station will stop the busy tone when collision occurs. The transmitting station can detect the collision by monitoring the busy tone of the destination. When the number of codes used in the network is K_2, the number of different busy tones required is also K_2. Each code has a corresponding busy tone and each station keeps a Code Table to record the codes and tones of all its neighbours. A tone is just a sinusoidal wave at a certain frequency which is different from the frequency used for data transmission. Therefore a station can receive data packets and transmits a busy tone at the same time.

(A) Transmission Protocol

(1) Find the code C_j and tone B_j of the receiving station from the Code Table and encodes the data packet using code C_j.
(2) Sense tone B_j. If tone B_j is detected, go to step (2) after a random delay. If tone B_j is not detected, transmit the packet immediately.
(3) During the packet transmission, if tone B_j is not detected in the time-out period or tone B_j terminates during the packet transmission, stop the transmission immediately, wait for a random delay and go to step (2).

(B) Reception Protocol

(1) When an incoming packet is detected in the station's assigned code C_j (i.e. after receiving the packet header), broadcast its assigned tone B_j during the period of packet reception.

(2) When the station detects a collision or error while receiving a packet, stop the busy tone immediately.

4. Simulation Results

Fourteen network samples are generated on which the performance of various protocols are compared. The stations in the network are randomly located within a 20 km×20 km square region. The transmission range is 4 km. The packet generation rates are the same for all stations and the packet destinations are equally probable for all stations, excluding the source station. Let the packets be of fixed length and let the arrivals to each station be a Poisson process. Minimum hop routing rule is used. The characteristics of the networks generated are summarized as follows:

	Network Samples						
	1	2	3	4	5	6	7
No. of stations N	80	80	80	80	80	80	80
avg. no. of neighbours per station	8.31	8.38	8.35	8.00	8.05	8.70	7.8
max. no. of neighbours per station	15	12	13	14	13	17	14
No. of codes K_1	21	15	15	15	14	18	16

	Network Samples						
	8	9	10	11	12	13	14
No. of stations N	40	40	40	40	40	40	40
avg. no. of neighbours per station	4.05	5.45	3.80	4.20	3.40	3.40	3.75
max. no. of neighbours per station	7	11	7	8	6	6	7
No. of codes K_1	9	14	8	9	7	7	8

Using the code assignment algorithm, the number of codes K_1 required without code interference is reduced to an average 22% of the total number of stations N. We denote the Coded Tone Sense protocol with n codes as CTS/n. In order to investigate the effect of code collision we have set n to be about one-third to one-fourth of K_1 and have chosen $n=5$ for the 80 station networks and $n=3$ for the 40 station networks in our examples. Note that n is the desired number of codes K_2 and CTS/1 is just the BTMA protocol. Using the code assignment algorithm on the Slotted ALOHA protocol, we have the Coded Slotted ALOHA (CSA/n) protocol. Except cases 2 and 9, we also compared CSA/n with CTS/n.

The normalized network throughput, or the average number of packets reaching the final destinations per packet transmission time is measured in the simulation. This throughput measure is different from the one-hop throughput usually given in some studies because most packets have to travel two or more hops before reaching their destinations. We assume the total bandwidth occupied by the busy tones is 2% of the total bandwidth for the CTS/n protocol. Note that a tone is just a pure sine wave at certain frequency and theoretically occupies zero bandwidth. In [11] we have designed two protocols which also use busy tones for detection and prevention of collisions, and we have shown that this 2% assumption is reasonable. The throughput shown for the CTS protocol is the effective network throughput, which is the normalized network throughput multiply by $(1-0.02)$. The average end-to-end delay as a function of network throughput for cases 1 and 8 are plotted in Figs. 2 and 3 respectively. The throughput-delay characteristics of other network samples are similar and so are not shown. The maximum network throughput attained for the fourteen station distributions (or the fourteen cases) are obtained as follows:

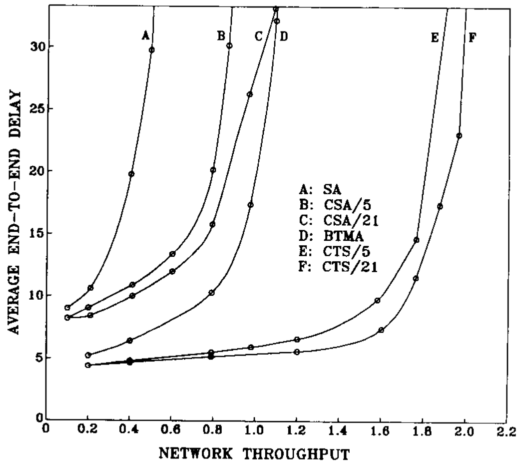

Fig. 2 Delay vs. throughput for a 80 node network.

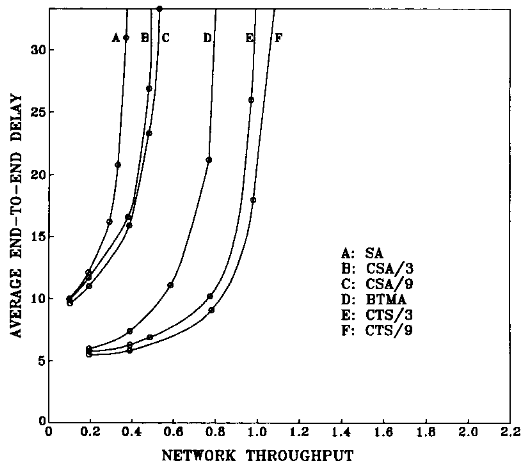

Fig. 3 Delay vs. throughput for a 40 node network.

Protocols	Network Samples						
	1	2	3	4	5	6	7
SA	0.50	-	0.51	0.40	0.38	0.41	0.42
CSA/n	0.90	-	0.90	0.86	0.70	0.68	0.86
CSA/K_1	1.10	-	1.11	1.00	0.81	0.83	1.06
BTMA	1.10	1.10	1.20	1.09	0.95	1.01	1.07
CTS/n	1.90	2.00	2.04	1.86	1.59	1.61	2.02
CTS/K_1	2.00	2.20	2.32	2.10	1.83	1.69	2.29

Protocols	Network Samples						
	8	9	10	11	12	13	14
SA	0.35	-	0.36	0.27	0.20	0.37	0.24
CSA/n	0.50	-	0.50	0.35	0.32	0.44	0.32
CSA/K_1	0.55	-	0.61	0.42	0.35	0.51	0.32
BTMA	0.80	0.80	0.85	0.67	0.57	0.86	0.57
CTS/n	1.00	1.00	1.11	0.82	0.71	0.99	0.73
CTS/K_1	1.10	1.20	1.30	0.89	0.73	1.09	0.74

The maximum network throughput of CTS/5 is found to be with average 73% higher than that of BTMA for the 80 station networks. For the 40 station networks, CTS/3 gives about 25% improvement. When the number of code groups is increased to K_1, there is only average 10% further improvement for the 80 station networks. For the 40 station networks, the further improvement is also about 10%. CTS/K_1 always have a smaller delay than CTS/n.

The maximum network throughput of CSA/n is found to be with average 88% higher than that of SA for cases of 80 station networks and 37% higher than that of SA for cases of 40 station networks. When the number of code groups is increased to K_1, there are 20% and 13% further improvements for cases with 80 and 40 stations respectively.

It can be concluded that there is a performance improvement of using more codes when the stations are densely located. For the 80 station networks using only 5 codes, the network performance is almost the same as those using 14 to 21 codes.

5. Conclusion

Using spread spectrum techniques in PRNs, overlapping of packet transmission is allowed by assigning a different code to each transmitted signal. We have designed an algorithm for assigning codes to the stations such that these codes can be reused beyond their interference range. This algorithm can reduce the number of speading codes required to 18%-35% of the total number of stations in the network.

Using the code assignment algorithm on Slotted ALOHA, the resulting CSA/n protocol can give 37% to 88% performance improvement over the SA protocol. We have also designed the Coded Tone Sense protocol which can further reduce the number of codes required. From simulation results, it was found that the CTS protocol has a much better performance than the BTMA protocol. For a 80 station network using only 5 codes, the maximum throughput of the CTS protocol is found to be 59% to 89% higher than that of the BTMA protocol.

It was found that the CSA and CTS protocols are particularly attractive for densely populated networks. For these networks only a few codes is sufficient to drive the thruoghput-delay performance very close to the case where each station has a unique code.

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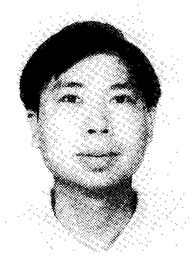

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