Self-Adaptive TDMA Protocols: A Learning-Automata-Based Approach

Georgios I. Papadimitriou and Andreas S. Pomportsis
Department of Informatics,
Aristotle University of Thessaloniki, Box 888,
54006 Thessaloniki, Greece.

Abstract

Due to its fixed assignment nature, the well-known TDMA protocol suffers from poor performance when the offered traffic is bursty. In this paper, a Learning-Automata-Based Time Division Multiple Access protocol, which is capable of operating efficiently under bursty traffic conditions, is introduced. According to the proposed protocol, the station which grants permission to transmit at each time slot is selected by means of learning automata. The choice probability of the selected station is updated by taking into account the network feedback information. The system which consists of the automata and the network is analyzed and it is proved that the choice probability of each station asymptotically tends to be proportional to the probability that this station is not idle. Thus, although there is no centralized control of the stations and the traffic characteristics are unknown and time-variable, each station tends to take a fraction of the bandwidth proportional to its needs. Furthermore, extensive simulation results are presented which indicate that the proposed protocol achieves a significantly higher performance than other well-known time division multiple access protocols when operating under bursty traffic conditions.

1. Introduction

The key issue in broadcast networks is how to determine who gets to use the channel. A broad range of Demand Assignment, Random Access and Fixed Assignment protocols have been proposed as solutions to this problem.

Demand Assignment protocols - such as Token Ring, Token Bus and DQDB [1],[2] - are based on a signaling procedure which allows certain network entities to be informed about the transmission and networking needs and demands of the network stations. Random Access protocols - such as ALOHA, CSMA and CSMA/CD [1],[2] - are characterized by the fact that stations contend for access to the communications channel, in accordance with an algorithm that can lead to colliding transmissions. All the collided packets are scheduled for retransmission. Fixed Assignment protocols - such as TDMA [2]-[8], RTDMA [9], [10] and FDMA [1] - assign a fixed portion of the available bandwidth to each station. In this way, collisions are avoided. Due to the absence of collisions, protocols of this family achieve a high performance when the traffic of each station is stable and a priori known. However, when the traffic is bursty, fixed assignment protocols are not capable of being adapted to the sharp changes of the stations' traffic. Therefore, their performance is dramatically degraded.

In this paper, a new time division multiple access protocol which is capable of operating efficiently under bursty traffic conditions is introduced. According to the proposed protocol, the station which grants permission to transmit is determined by means of learning automata [11]-[16]. At each time slot, the automata take into account the network feedback information in order to update the choice probability of the selected station. The learning algorithm was designed in such a way, that the choice probability of each station asymptotically tends to be proportional to the probability that this station is not idle. In this way, the number of idle slots is minimized and the network performance is significantly improved. When the traffic conditions of a station change, this leads to a change of the choice probability of this station. Therefore, the protocol is capable of being adapted to the sharp load changes of a bursty traffic environment.

The proposed Learning-Automata-Based Time Division Multiple Access (LTDMA) protocol is applicable to a broad range of broadcast network architectures, including bus, star and wireless LANs. This paper focuses on the theoretical aspects of LTDMA rather than on its application to specific network architectures.

The paper is organized as follows: The proposed LTDMA protocol is presented in Section 2, while an analysis of the asymptotic behavior of the system which consists of the automata and the network is presented in Section 3. In Section 4, extensive simulation results are presented which indicate the superiority of the LTDMA

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protocol over other well-known TDMA protocols. Finally, concluding remarks are given in Section 5.

2. The LTDMA Protocol

According to the LTDMA protocol, each station is provided with a learning automaton which contains the basic choice probability $P_i(t)$ of each station u_i for $i = 1, \ldots, N$, where N is the number of stations. At each time slot t, the basic choice probabilities are normalized in the following way:

$$\Pi_i(t) = \frac{P_i(t)}{\sum_{k=1}^{N} P_k(t)} \tag{1}$$

Obviously, $\sum_{i=1}^{N} \Pi_i(t) = 1$. The station which grants permission to transmit is selected according to the normalized probabilities $\Pi_i(t)$, for $i = 1, \ldots, N$.

At each time slot t, the basic choice probability $P_i(t)$ of the selected station $u(t) = u_i$ is updated according to the network feedback information. If station u_i transmitted a packet during time slot t, then the basic choice probability of u_i increases. Otherwise, if the selected station u_i was idle, then the basic choice probability of u_i decreases. The following probability updating scheme is used (where: $L, a \in (0,1)$ and $P_i(t) \in (a, 1)$ for all t):

$$\begin{aligned} P_i(t+1) &= P_i(t) + L(1 - P_i(t)) \\ &\quad \text{if } u(t) = u_i \text{ and } slot(t) = success \\ P_i(t+1) &= P_i(t) - L(P_i(t) - a) \\ &\quad \text{if } u(t) = u_i \text{ and } slot(t) = idle \end{aligned} \tag{2}$$

Since the offered traffic is bursty, when the selected station has a packet to transmit, it is probable that this station will have packets to transmit in the near future. Therefore, its choice probability is increased. On the other hand, when the selected station is idle, it is probable that this station will remain idle in the near future. Therefore, its choice probability is decreased.

When the choice probability of a station converges to 0, then this station is not selected for a long period. During this period, it is probable that the station transits from idle to busy state. However, since the station does not grant permission to transmit, the automata are not capable of "sensing" the transition. The role of parameter a, is to prevent the choice probabilities of the stations from taking values in the neighborhood of 0, in order to increase the adaptivity of the protocol.

All the stations use the same learning algorithm and - due to the broadcast nature of the network - the network feedback information is common for all the stations. Consequently, all the automata always contain the same choice probabilities. Furthermore, since the same random number generator and the same seed is used by all the stations, it follows that all the stations select the same station which grants permission to transmit [9]. Therefore, although there is not centralized coordination between the stations, the protocol is collision-free.

3. Analysis

Theorem 1. If the learning algorithm (2) is used and d_i is the probability that station u_i is not idle (for $i = 1, \ldots, N$), then for any station u_i:

$$\lim_{t\to\infty, L\to 0, a\to 0} P_i(t) = d_i$$

Proof. To prove Theorem 1, we shall use the following theorem, which is presented in [16].

Let $x(t)_{t\geq 0}$ be a stationary Markov process dependent on a constant parameter $\theta \in [0,1]$. Each $x(t) \in I$, where I is a subset of the real line. Let $\delta x(t) = x(t+1) - x(t)$. The following are assumed to hold:
(i) I is compact.
(ii) $E[\delta x(t) | x(t) = y] = \theta\, \omega(y) + O(\theta^2)$.
(iii) $E[|\delta x(t)|^2 \mid x(t) = y] = \theta^2\, b(y) + O(\theta^2)$.
(iv) $E[|\delta x(t)|^3 \mid x(t) = y] = O(\theta^3)$, where:

$$\sup_{y\in I} \frac{O(\theta^k)}{\theta^k} < \infty \text{ for } k = 2, 3 \quad \text{and} \quad \sup_{y\in I} \frac{O(\theta^2)}{\theta^2} \to 0 \text{ as } \theta \to 0$$

(v) $\omega(y)$ has a Lipschitz derivative in I.
(vi) $b(y)$ is Lipschitz in I.

Theorem 2. If assumptions (i)-(vi) hold, $\omega(y)$ has a unique root y^* in I and $d\omega/dy|_{y=y^*} < 0$, then:
(a) $var[x(t)|x(0) = x] = O(\theta)$ uniformly for all $x \in I$ and $t \geq 0$.
(b) For any $x \in I$ the differential equation $\frac{dy(\tau)}{d\tau} = \omega(y(t))$ has a unique solution $y(\tau) = y(\tau, x)$ with $y(0) = x$ and $E[x(t)|x(0) = x] = y(t\theta) + O(\theta)$ uniformly for all $x \in I$ and $t \geq 0$.
(c) $(x(t) - y(t\theta))/\sqrt{\theta}$ has a normal distribution with zero mean and finite variance as $\theta \to 0$ and $t\theta \to \infty$.

To apply the above theorem to the proof of Theorem 1, we have to identify $x(t)$ with $P_i(t)$, θ with L and I with $(a, 1)$. We have:

$$\begin{aligned} &E[\delta P_i(t) | P_i(t) = P_i] \\ &= \frac{P_i}{\sum_{k=1}^{N} P_k} (d_i L(1 - P_i) - (1 - d_i) L(P_i - a)) \\ &= L \frac{P_i}{\sum_{k=1}^{N} P_k} (-P_i + d_i + a(1 - d_i)) = L\omega(P_i) \end{aligned} \tag{3}$$

$$E[|\delta P_i(t)|^2|P_i(t) = P_i]$$
$$= L^2 \frac{P_i}{\sum_{k=1}^{N} P_k}(d_i(1-P_i)^2+(1-d_i)(P_i-a)^2) = L^2 b(P_i) \quad (4)$$

$$E[|\delta P_i(t)|^3|P_i(t) = P_i]$$
$$= L^3 \frac{P_i}{\sum_{k=1}^{N} P_k}(d_i(1-P_i)^3+(1-d_i)(P_i-a)^3) = O(L^3) \quad (5)$$

The functions $\omega(P_i)$ and $b(P_i)$ are defined as follows:

$$\omega(P_i) = \frac{P_i}{\sum_{k=1}^{N} P_k}(-P_i + d_i + a(1-d_i)) \quad (6)$$

$$b(P_i) = \frac{P_i}{\sum_{k=1}^{N} P_k}(d_i(1-P_i)^2 + (1-d_i)(P_i - a)^2) \quad (7)$$

It is immediately seen that assumptions (i)-(iv) are satisfied. It can also be proved that $b(P_i)$ and $\omega'(P_i)$ are Lipschitz in (a,1) by showing that their first derivatives ($b'(P_i)$ and $\omega''(P_i)$ correspondingly) are bounded [17] for $P_i \in (a, 1)$.

It remains to show that $\omega(P_i)$ has a unique root P_i^r near the point $P_i^* = d_i$ and that $d\omega(P_i)/dP_i|_{P_i=P_i^r} < 0$. It is immediately seen that $\omega(P_i)$ has a unique root at the point $P_i^r = d_i + a(1-d_i)$. Since a can be arbitrarily small, it follows that P_i^r is in the neighborhood of the point $P_i^* = d_i$. The derivative of $\omega(P_i)$ at this point is:

$$\frac{d\omega(P_i)}{dP_i}|_{P_i=P_i^r} = \frac{d\left(\frac{P_i}{\sum_{k=1}^{N} P_k}(-P_i+d_i+a(1-d_i))\right)}{dP_i}|_{P_i=P_i^r}$$
$$= -\frac{1}{1+\frac{\sum_{k=1,k\neq i}^{N} P_k}{P_i^r}} < 0 \quad (8)$$

It has been shown that $\omega(P_i)$ has a unique root P_i^r in the neighborhood of the point $P_i^* = d_i$ and that the derivative of $\omega(P_i)$ at this point is negative.

If we set $P_i(\tau) = P_i^r$, the differential equation $\frac{dP_i(\tau)}{d\tau} = \omega(P_i(\tau))$ is satisfied (0=0). Thus, $P_i(\tau) = P_i^r$ is a solution of the above differential equation. From Theorem 2, it is derived that this solution is unique, thus all the solutions starting in $(a, 1)$ of the differential equation $\frac{dP_i(\tau)}{d\tau} = \omega(P_i(\tau))$ converge to the point $P_i(\tau) = P_i^r \simeq P_i^* = d_i$. According to Theorem 2, we have:

$$\lim_{t\to\infty, a\to 0} E[P_i(t)] = P_i^* + O(L)$$

and

$$var[P_i(t)] = O(L) \qquad \text{for all } t.$$

Consequently,

$$\lim_{t\to\infty, L\to 0, a\to 0} P_i(t) = d_i \qquad \text{q.e.d.} \quad (9)$$

The exact values of a and L depend on the environment where the automata operate. When the environment is slowly switching or when the environmental responses have a high variance, a and L must be very close to 0 in order to guarantee a high accuracy. On the other hand, in a rapidly switching environment or when the variance of the environmental responses is low, higher values of a and L can be used, in order to increase the adaptivity of the protocol. Thus, when the burst length is high or the queue length is low, then small values of a and L must be selected. On the other hand, when the burst length is low or when the queue length is high, then a and L can be much higher.

According to Theorem 1, for any two stations u_i and u_j (with $d_j \neq 0$), the LTDMA asymptotically tends to satisfy the relation:

$$\frac{P_i}{P_j} = \frac{d_i}{d_j} \quad (10)$$

This relation also holds for the normalized choice probabilities Π_i and Π_j:

$$\frac{\Pi_i}{\Pi_j} = \frac{\frac{P_i}{\sum_{k=1}^{N} P_k(t)}}{\frac{P_j}{\sum_{k=1}^{N} P_k(t)}} = \frac{P_i}{P_j} = \frac{d_i}{d_j} \quad (11)$$

Therefore, each station tends to take a fraction of the available bandwidth, proportional to the probability that this station is not idle. Therefore, the portion of the bandwidth which is assigned to each station tends to be proportional to the station's needs.

4. Simulation Results

In the following, the proposed LTDMA protocol is compared to TDMA [2]-[8] and RTDMA [9],[10]; two representative time division multiple access protocols. The protocols which are under comparison were simulated to be applied to four different networks (N_1, N_2, N_3 and N_4) under bursty traffic conditions. The bursty traffic was modelled in a way similar to the ones presented in [19] and [20]. Each node can be in one of two states S_0 and S_1. When a node is in state S_0 then it has no packet arrivals. When a node is in state S_1 then at each time slot it has a packet arrival with probability Z. Given a station is in state S_0 at time slot t, the probability that this station will transit to state S_1 at the next time slot is P_{01}. The transition probability from state S_1 to state S_0 is P_{10}. It can be shown that, when the load offered to the network is R packets/slot and the mean burst length is B slots, then the transition probabilities are: $P_{10} = 1/B$ and $P_{01} = \frac{R}{B(NZ-R)}$.

The number of users N, the queue size Q, the mean burst length B and the packet arrival probability Z of each active station, were taken to be as follows:

a) Network $N_1: N = 10, Q = 10, B = 10, Z = 1.0$

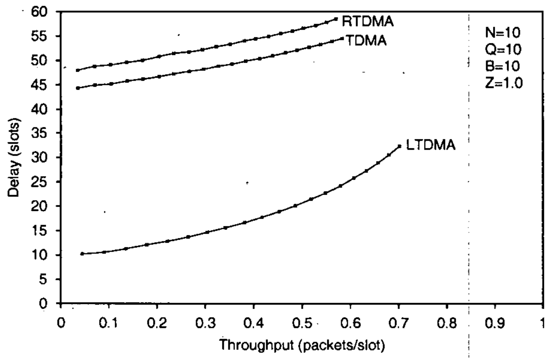

Figure 1: The Delay versus Throughput characteristics of LTDMA, TDMA and RTDMA when applied to network N_1.

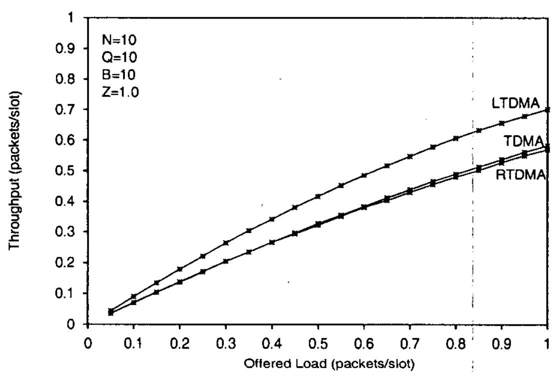

Figure 2: The Throughput versus Load characteristics of LTDMA, TDMA and RTDMA when applied to network N_1.

b) Network $N_2 : N = 10, Q = 3, B = 200, Z = 0.7$

c) Network $N_3 : N = 20, Q = 15, B = 10, Z = 1.0$

d) Network $N_4 : N = 5, Q = 3, B = 1000, Z = 0.8$

We have used the following two broadly used performance metrics in order to compare the three protocols:

1) The delay versus throughput characteristic.

2) The throughput versus offered load characteristic.

The delay versus throughput characteristics of the compared protocols when they are applied to networks N_1, N_2, N_3 and N_4 are appeared at figures 1, 3, 5 and 7, correspondingly. The throughput versus offered load characteristics of the compared protocols when they are applied to networks N_1, N_2, N_3 and N_4 are appeared at figures 2, 4, 6 and 8, correspondingly.

From the above graphs, it becomes clear that, LTDMA

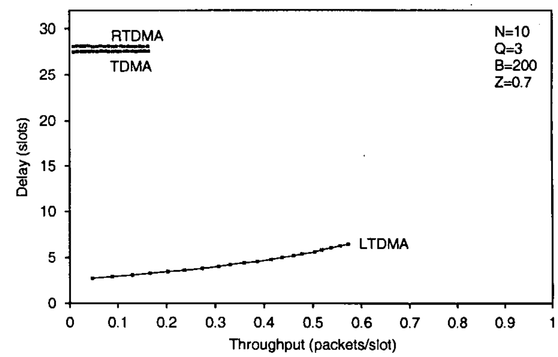

Figure 3: The Delay versus Throughput characteristics of LTDMA, TDMA and RTDMA when applied to network N_2.

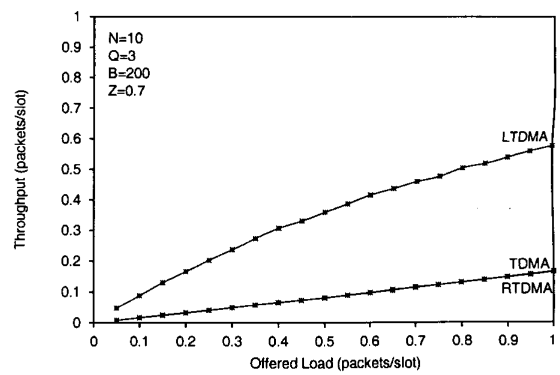

Figure 4: The Throughput versus Load characteristics of LTDMA, TDMA and RTDMA when applied to network N_2.

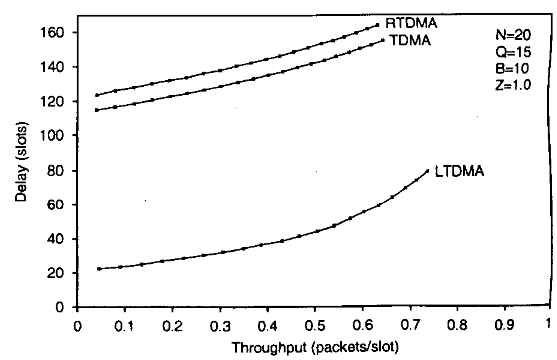

Figure 5: The Delay versus Throughput characteristics of LTDMA, TDMA and RTDMA when applied to network N_3.

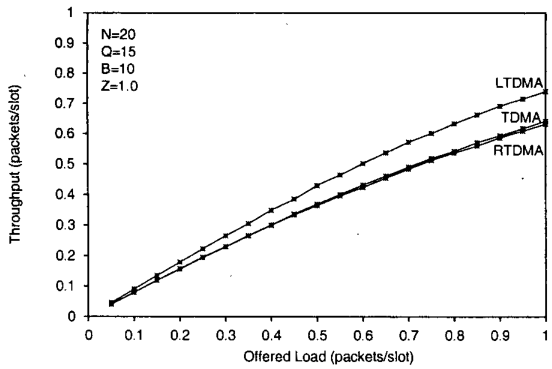

Figure 6: The Throughput versus Load characteristics of LTDMA, TDMA and RTDMA when applied to network N_3.

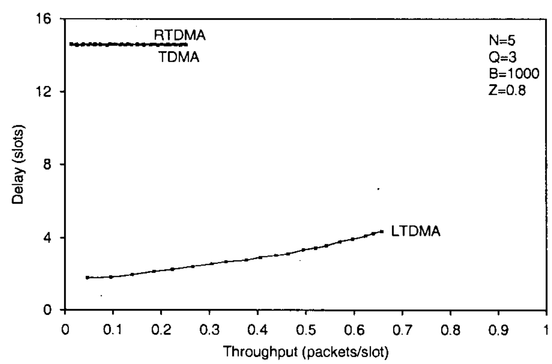

Figure 7: The Delay versus Throughput characteristics of LTDMA, TDMA and RTDMA when applied to network N_4.

achieves a significantly higher delay-throughput and throughput-load performance than protocols TDMA and RTDMA, when operating under bursty traffic conditions. The performance improvement which is achieved by the use of LTDMA is higher when the offered traffic is more bursty (i.e. when the mean burst length is high).

5. Conclusion

This paper has presented a new time division multiple access protocol for broadcast networks. According the proposed LTDMA protocol, the station which grants permission to transmit at each time slot is selected by means of learning automata, which are capable of being adapted to the changes of the stations' traffic. Therefore, the new protocol

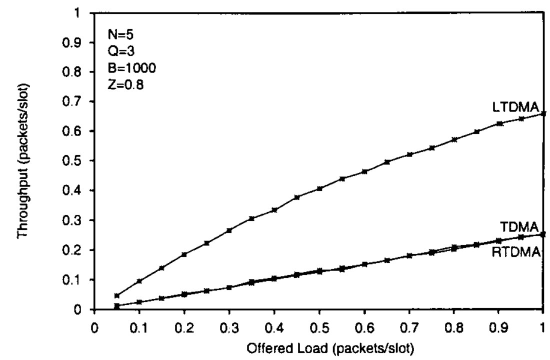

Figure 8: The Throughput versus Load characteristics of LTDMA, TDMA and RTDMA when applied to network N_4.

is capable of achieving a low delay and a high throughput in the dynamic bursty traffic environment.

The main characteristics of the LTDMA protocol are summarized below:

a) It achieves a high performance, even when the offered traffic is bursty.

b) The protocol is self-adaptive. Each station tends to take a fraction of the available bandwidth proportional to its needs. Furthermore, when a station goes down for a long period, its choice probability converges to a and consequently, the available bandwidth is shared between the other stations.

c) No centralized control of the stations is required, since the protocol is fully distributed.

d) It is fault-tolerant, since its operation is not affected from a possible node failure.

e) No significant increase of the implementation cost is introduced. The only additional hardware - in relation to TDMA or RTDMA - is a processor which implements the learning algorithm.

The use of learning automata offers a new highly promising approach to the design of self-adaptive multiaccess protocols for broadcast networks. We are currently working on this direction.

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