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Abstract-In this paper we describe a new medium access protocol termed as the modified grouped-tag TDMA protocol (MGTDMA) for networking radio frequency identification tags. It is known that the previously proposed grouped-tag TDMA (GTDMA) protocol performs very well under the conditions of uniform destination distribution and not so well for heterogeneous traffic conditions. The MGTDMA differs from GTDMA in the sense that MGTDMA allows groups experiencing high traffic to steal (cooperatively) from low traffic groups at regular time intervals. Performance of an access scheme is assessed in terms of average packet delay and average energy consumption. Approximate analytical equation for average delay is derived. More accurate estimates for delay are obtained through simulation studies. We compare the performances of MGTDMA, GTDMA, and a pseudo random protocol and show the usefulness of the new scheme.

I. Introduction

Tags are small radio frequency devices capable of receiving, and some times transmitting, small sized messages. Depending on application, they are also capable of performing some limited calculations. A number of applications involving such tags are mentioned in a recent paper [1]. Some of these are the following: location tracking of livestock, smart tags used in warehouses to track inventory, and numerous tag companies targeting retail market. A radio frequency identification devices (RFID) network typically would employ a large number of such tags. Typically, the tags do not communicate among themselves. The tags are operated by tiny built-in batteries such that, at the end of a battery life period, the tag itself has to be thrown out. Therefore, the price of each tag has to be necessarily low. Up link transmission from tags to a base station in an RFID network would require much more energy than the reception of a message from the base station. Hence, the transmission from a tag is employed only in some applications, and that too in limited situations. Furthermore, limited unlicensed bandwidth and the simplicity of the tag means that all tags must share the same broadcast band. The above reasons put unique constrains in terms of low delay and low energy consumption on an RFID network. In this paper we restrict our attention to base to tags communication only.

In reference [1], Chlamtac et al considered three protocols, namely a grouped-tag TDMA (GTDMA), a pseudo random protocol, and a directory protocol for medium access from base to tag communications. In order to minimize energy consumption, the tags go cyclically through awake and sleep modes. If a tag is awake when a packet addressed to it is ready at the base station, then that packet is assumed successfully sent from the base station. Otherwise the packet has to wait in the queue at the base station. In performance analysis, the channel between the base and a tag is assumed perfect and no channel errors are considered. Approximate analytical equations for delay were derived for the three protocols. Their results reveal that the GTDMA performs very well, in terms of low delay for a given energy consumption, under the condition of homogeneous destination traffic condition. For heterogeneous traffic, when certain tags receive more packetized data than others, the pseudo random protocol performs better than GTDMA. Moreover, the GTDMA becomes unstable for low energy and high traffic arrival rates conditions. In this paper we propose a modified grouped-tag TDMA (MGTDMA) so that the modified scheme could perform better than the GTDMA under heterogeneous traffic situations.

II. MGTDMA

In GTDMA the tags are grouped into m groups, each with $x = \lfloor N/m \rfloor$ tags in them. Here N denotes the number of tags in the network. A time slot approximately equals a packet length (plus a negligible propagation delay). The base station TDMA frame has m slots. Once in every frame, during an assigned slot, the tags in a particular group wake up, whereas the others will be in sleep mode. If any of the tags in that awake-group has a packet ready to be delivered at the base station, then that packet will be successfully sent during that time slot. The normalized energy consumption (fraction of the time a tag is awake) in GTDMA is, $E = \frac{1}{m}$. Regular TDMA is a special case of GTDMA with m=N. Hence, compared to TDMA, GTDMA consumes x times the energy of TDMA, but cuts down the delay because of increased throughput. The MGTDMA is based on the following approach: allow tags with high traffic to "steal" periodically slots from the tags with low traffic. In general, a high traffic tag can steal b slots per frame, once in every L frames, from b low traffic tags. The base station has to monitor the traffic conditions and then designate the low and high traffic tags. Other tags, which do not belong to these two categories, can be designated as moderate traffic

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tags. The tag designations need to be communicated to the tags, as and when the traffic patterns change, so that each tag could identify their sleeping states. The tag, which lends its slot during a frame, does not wake up during that slot. Instead, the tag, which "steals" the slot, wakes up in that slot. It is clear that, on an average, the normalized energy is the same as that of GTDMA, even though a high traffic tag would consume more energy than a low traffic tag. We assume in the analysis that there are 2z high traffic (and hence b(2z) low traffic slots) in every frame. Also, the destination traffic distribution was assumed to be Gaussian [1]. By controlling the variance of the Gaussian distribution, it is possible to approximate a range of distributions from uniform (high variance) through highly peaked distribution (low variance).

2.1 Average Delay Approximation for MGTDMA

In MGTDMA, the tag groups are divided into three classes, namely, class 1 of high traffic frequency tags(HTT), class 2 of low traffic frequency tags(LTT) and class 3 of moderate traffic frequency tags(MTT). Let λ denote the average packets arrival rate in the system(measured in number of packets per slot). Let p_i denote the probability that a newly arrived packet is addressed to a tag in the i^{th} group. It is given by

$$p_i = \frac{F\left(\frac{iN}{m}\right) - F\left(\frac{(i-1)N}{m}\right)}{F(N) - F(0)}, i = 1,2,..,m, \qquad (1)$$

where $F(.)$ represents the cumulative distribution function of Gaussian with mean $N/2$ and an appropriate variance (variance of N and 10 N are considered for numerical evaluation). In the above equation, for HTT tags, $i \in \left\{\frac{m}{2}-(z-1), \frac{m}{2}-(z-2),.., \frac{m}{2}, \frac{m}{2}+1,.., \frac{m}{2}+z\right\}$ and for LTT tags, $i \in \{(1,2,..,bz) U (m, m-1,.., m-b(z-1))\}$. By placing the HTT groups in the center of the Gaussian distribution and the LTT groups in the tails of the distribution, we guarantee appropriate traffics for these groups. Also, observe that several groups of tags could belong to a class, say HTT, but the traffic rates for all the groups within the class need not be identical.

In GTDMA [4], if we calculate the waiting time in queue and recognize that the services are all equal to 1 frame (m slots), then the system can be described by an M / D / 1 queue with vacations. In the case of MGTDMA, M / D / 1 with vacations is not strictly applicable. The service times differ, depending on which frame a customer arrives. Following the approach in [2], we obtain an expression to approximately estimate the delay in an MGTDMA scheme. As in [2], let W_i denote the waiting time in queue for the i^{th} customer, N_i denote the number of customers found waiting in queue by the i^{th} customer upon arrival, and let R_i denote the residual service time seen by the i^{th} customer. The service time for the j'th arrival will be denoted by X_j. If no customer is in service when i^{th} customer arrives, then the server will be on vacation. The vacation time is denoted by V_i. V_i will be equal to the time between the previous access time and the next one. By closely examining the two time lengths X_j, V_i, it is obvious that they are identical, but the first occurs when the server is busy and the latter occurs when the system is idle (on vacations). From [2], we obtain the following equation:

$$W_i = R_i + \sum_{j=i-N_i}^{i-1} X_j \quad . \qquad (2)$$

By taking expectations on both sides, we get

$$Å\{W\} = Å\{R_i\} + Å\{X_{i-N_i} + \cdots + X_{i-1}\}. \qquad (3)$$

As seen in Fig. 1, the service length is different. In order to calculate the services, we require the knowledge of the number of customers in the system at the arrival instant of the i^{th} customer. Since the queue length distribution is difficult to arrive at, we approximate (3) as

$$E\{W_i\} \approx E\{R_i\} + E(X) \cdot E(N_i) \qquad (4)$$

This approximation is not strictly valid, as the second term on the right hand side of (3) cannot in general be replaced by $E(X) \cdot E(N_i)$. However, when the number of customers in service is either very large or very small, then the approximation provides better estimates for the delays. We verified this by comparing the results from simulation for low values of λ. By using steady state operation and Little's theorem as in [2], we get

$$W \approx \frac{R}{1-\rho} \qquad (5)$$

where R is the mean residual time, $\rho = \frac{\lambda}{\mu}$ is the utilization factor, and $\mu = \frac{1}{E(X)}$ is the mean service rate, when the server is constantly busy. The average delay is then given by

$$T = W + 1. \qquad (6)$$

Because the tags were divided into three different categories, with each category claiming a different service rate, three different sets of equations are necessary. The MTTs retain the behavior of the GTDMA and as a result the equations in [1] apply. The HTT and LTT have different service rates and so new equations must be obtained.

2.1.1 The HTTs

By following [2], we can calculate R by a graphical argument. The only difference is that in our case, the service time or the vacation time is not random, but is merely one of several, say y, possible values (see Fig. 1). Given the total number of tags m and the number of tags in each class, it is possible to calculate all of these possible values. Even though these times are fixed values, a randomly arriving customer will see one of these with certain probability.

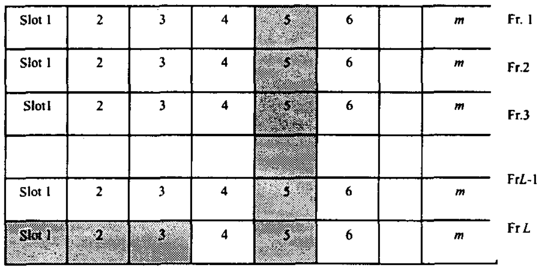

Figure 1. Timing Configuration for b=3 and 2z=1.

Therefore, a probability distribution can be associated with these variables, X and V. As mentioned earlier, both will have identical distributions. Proceeding as in [2], we get

$$R=\frac{1}{t}\cdot\sum_{i=1}^{M(t)}\frac{1}{2}\cdot\overline{X_i^2}+\frac{1}{t}\cdot\sum_{i=1}^{L(t)}\frac{1}{2}\cdot\overline{V_i^2} \tag{7}$$

The residual vacation term in (7) can be shown to be equal to (see [3])

$$\frac{1}{t}\cdot\sum_{i=1}^{L(t)}\frac{1}{2}\cdot\bar{V}_i^2=\frac{(1-\rho)}{2}\cdot\sum_{i=1}^{y}P_i\cdot V_i \tag{8}$$

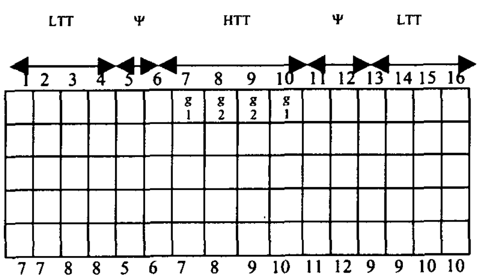

Figure 2. Timing Configuration for 4 High Traffic (2z=4)

Groups Which Steal Twice (b=2) Every L Frames

where V_i are possible vacations with P_i denoting the corresponding probabilities. Figures 1 and 2 show two situations corresponding to two different values of 2z. Corresponding to Fig. 2, the different groups of HTT occupy different positions within a frame, and therefore the vacation times for these groups would be different. These times can be calculated in terms of the position index variable g, as shown in Fig. 2. Also, 2ψ denote the number of MTT groups in the system. It equals (m-2z(b+1)).

Similarly, the first term on the right hand side of (7) equals

$$\frac{1}{t}\cdot\sum_{j=1}^{M(t)}\frac{1}{2}\cdot\bar{X}_j^2=\frac{\rho}{2}\cdot\left(\sum_{j=1}^{x}X_j\cdot P_j\right) \tag{9}$$

X_j and V_i have identical distributions as shown in Fig. 3. Using (8) and (9) in (7) yields

$$R=\frac{\sum_{i=1}^{y}P_iX_i}{2}=\frac{\sum_{i=1}^{y}P_iV_i}{2} \tag{10}$$

2.1.2 The LTT's

Using Fig. 1 and Fig. 2, we can identify that the vacation interval of a LTT for the first $L-1$ frames is m. In the L^{th} frame, the right to send is lost though, hence the vacation or service for this frame is twice as long ($2\cdot m$). The vacation distribution is given by

$$P(V_i=m)=(L-1)/L$$
$$P(V_i=2m)=1-P(V_i=m) \tag{11}$$

Equation (10) applies to this case, with the distribution in Fig. 3 replaced by (11).

2.1.3 The MTT's

Average delay T_{3i} corresponds to that of a regular GTDMA tag[1]:

$$T_{3i}=W_{3i}+1 \tag{12}$$

$$W_{3i}=\frac{m}{2(1-\lambda\, p_i m)} \tag{13}$$

The average delay for MGTDMA is then given by

$$T=\sum_{i\in(\text{Class 1})}T_{1i}\,p_i+\sum_{i\in(\text{Class 2})}T_{2i}\,p_i+\sum_{i\in(\text{Class 3})}T_{3i}\,p_i \tag{14}$$

where T_{1i}, T_{2i} are the average delays for HTT and LTT groups, respectively. Using (5), (6), and (10), we get

$$T_{1i}=R/(1-\lambda\, p_i/\mu)+1\,, \tag{15}$$

where $\mu=(Lm)/(L+b)$ and the distributions for V, X are given in Fig. 2.

Similarly, T_{2i} is given by (15), with the distribution for V, X given by (11) and $\mu = (L+1)m/L$.

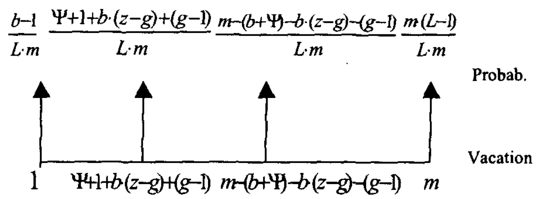

Figure 3. Vacation Time Distribution

2.2 *MGTDMA Simulation*

More accurate estimates of average delay in MGTDMA are possible through a simulation study. A code in C was written for this purpose[3]. The packet arrivals were simulated using a Poisson arrival process. Results from the simulation for the cases of pseudo random protocol and GTDMA protocol showed excellent agreements with the results in [1].

III. Results and Discussion

The results discussed below are those obtained from simulation. The results from the approximate analytical study were also computed and compared against the simulation results. As said earlier, because of the approximation involved in arriving at (4), we expect the analytical solution to be accurate only under restricted conditions. The analytical results obtained were approximately 1% off with the simulation results for all types of destinations, λ=0.05, λ=0.2 and $m \leq 20$. For the cases of λ=0.2 given $m > 20$ and λ=0.5, the results were off by 5 to 15 %.

In Figures 4 through 6 we compare the performances of GTDMA, MGTDMA and pseudo random (PR) protocols under heterogeneous traffic conditions (i.e., Gaussian tag destination distribution variance of N). Only one HTT group was assumed ($2z$=1) with no MTT groups and with b set at (m-1). For a low arrival rate of 0.05 packets per slot (Fig. 4), MGTDMA both L=2 and 4 perform about the same. MGTDMA outperforms both GTDMA (GTDMA is a special case of MGTDMA with $L = \infty$) and PR. For an average energy of 0.075, average delay of MGTDMA is about half of that of GTDMA. When arrival rate equals 0.2, MGTDMA significantly outperforms GTDMA and it shows lower average delay than PR for a broad range of average energy values. Only for very low energy values(less than 0.03), the PR outperforms MGTDMA. Another observation is that L=2 provides a lower delay than L=4. Since the average traffic is not low and the traffic is heterogeneous (LTT has negligible traffic as compared to the single HTT group), more frequent stealing of slots, once every two frames (L=2), is beneficial in reducing average delays. In Fig. 6, the traffic is relatively heavy. MGTDMA with L=2 outperforms PR only over high values of energy(exceeding 0.075). This shows that even though MGTDMA performs significantly better than GTDMA and PR under heterogeneous traffic for moderate average traffic rates, for heavy traffic, MGTDMA becomes unstable. Under heavy traffic PR performs the best. For near homogeneous traffic (i.e., Gaussian variance of 10N), we show only a representative result, Fig. 7. In this case, for MGTDMA, we set $2z = m/3$ and b=2. For a packet arrival rate of 0.2, GTDMA outperforms both MGTDMA and PR. In this case, stealing is detrimental as the so called LTT tags also receive significant traffic, and stealing slots from them only causes increased overall average delays.

IV. Conclusions

We observed that the proposed MGTDMA provides better energy/ delay tradeoffs than GTDMA, especially for low variance Gaussian destination distribution. For low and moderate arrival rates, it also performs better than a pseudo random protocol. It is also observed that the design values are achievable. That is, the parameters L and b can be chosen so as to achieve a reasonable performance over a wide range of traffic conditions. Finally, we observed that, even though MGTDMA performs better than GTDMA, MGTDMA protocol also becomes unstable for higher arrival rates. The pseudo random protocol performs the best under high arrival rates.

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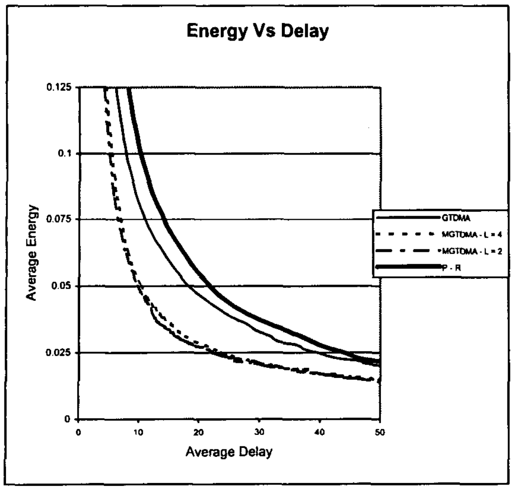

Figure 4. Comparison of Pseudo-random, GTDMA and MGTDMA, Gaussian ($\sigma = \sqrt{N}, \mu = N/2$) Destination and $\lambda = 0.05$.

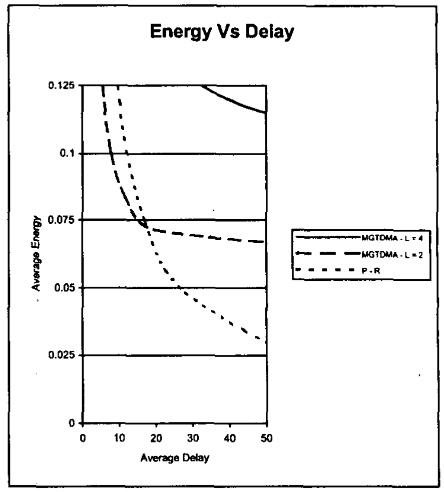

Figure 6. Comparison of Pseudo-random and MGTDMA,

Gaussian ($\sigma = \sqrt{N}, \mu = N/2$) Destination and $\lambda = 0.3$

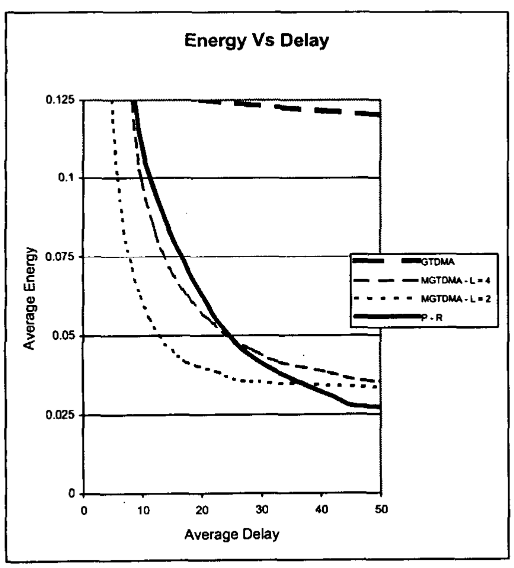

Figure 5. Comparison of Pseudo-random, GTDMA and MGTDMA, Gaussian ($\sigma = \sqrt{N}, \mu = N/2$) Destination and $\lambda = 0.2$

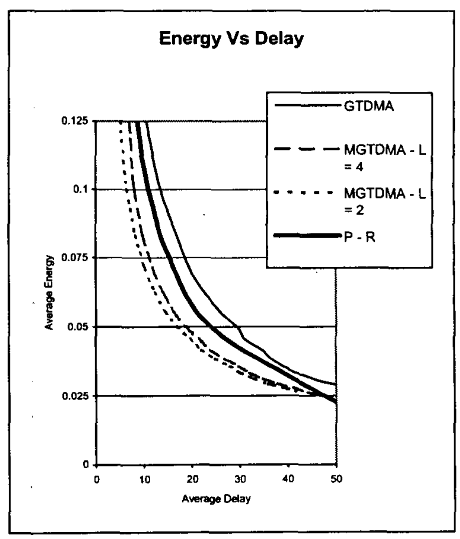

Figure 7. Comparison of Pseudo-Random, GTDMA and MGTDMA, Gaussian ($\sigma = \sqrt{10 \cdot N}, \mu = N/2$) Destination and $\lambda = 0.2$.