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A QoS-aware MAC Protocol for Multimedia WSNs

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Abstract: As multimedia or visual WSN has contributed to new application areas, apart from power consumption, performance and QoS assurances, such as end to end delay, priorities differentiation are becoming crucial as opposed to the best-effort performance in traditional monitoring applications. Two-level Parallel Wireless Token Ring Protocol (TPWTRP) is introduced for priority-based delay sensitive collision-free channel access in WSNs, which uses parallel 1-limited and Exhaustive services to realize the priority-based scheme. A polling network model is proposed for mean queue length and information packet waiting time analysis. Theoretical and simulation results are identical and show that the new system efficiently differentiates priorities and meets the practical demands of priority based applications well.

Key words: Wireless sensor networks, MAC, delay guarantee, priority differentiation

INTRODUCTION

A Wireless Sensor Network (WSN) consists of many small, cheap and low-power sensor nodes that use wireless technology (usually radio) to communicate with each other (Akyildiz *et al*., 2002). The early research on WSNs has mainly focused on monitoring applications with low-rate data collection (Wark *et al*., 2007, Mainwaring *et al*., 2002). Energy consumption attracts most of the attention in MAC protocol research. In the last few years, several low-power Medium Access Control (MAC) protocols have been proposed (Wei *et al*., 2002; Anastasi *et al*., 2009). Hardly any attention has been given to the delay guarantee of the network. However, with the availability of low-cost hardware and rapid development of tiny cameras and microphones, delay sensitive multimedia applications like multimedia or visual wireless sensor networks (Akyildiz *et al*., 2007; Soro and Heinzelman, 2009) and this new class has become a new tendency in potential WSN applications.

WSNs inherit most of the well-known QoS challenges from traditional wireless networks, such as Resource constraints, Topology changes, real-time traffic, unbalanced traffic, et al. MAC layer possesses a particular importance among the entire communication protocol stack since it rules the sharing of the medium and all other upper layer protocols are bound to that.

Depending on the application requirements, there are three basic data delivery models: Continuous, query driven and event-driven model in WSN (Tilak *et al*., 2002). Table 1 contains the main metrics that can be fulfilled at MAC for different application classes whereas other metrics such as maximizing throughput, minimizing end to end delay from source nodes to sink node can be considered for the whole protocol stack. It associates to parameters include transmission time, duty cycle, queuing mechanisms, *et al.* at MAC layer (Yigitel *et al*., 2011).

Table 1: Important MAC layer QoS metrics for application classes

Qos metric	Event driven	Query driven	Cont.	Hybrid
Medium access delay	√	√		√
Reliability	√	√		√
Energy consumption	√	√	√	√
Adaptivity	√	√		√

In some critical applications like natural disaster monitoring or security surveillance, gathered data is valid only for a limited time frame and has to be delivered rapidly. Critical real-time data must be handled by adequate QoS mechanisms. Polling is a typical sample of query driven delivery model (Levy and Sidi, 1990). It reduces the number of retransmissions due to collisions and realizes the real-time traffic. Node mobility, link failures, node malfunctioning, energy depletion or natural events can cause topology changes, however, polling mechanism is less effect in node deployment and topology changes because of the central control scheme. Mustafa introduced the ring set up, ring management, node states of WTRP (wireless token ring protocol) (Ergen *et al*., 2004). In WTRP, nodes in a ring acquire the token circularly passes in a logic ring and each node transmit data packets in the buffers in a same service discipline, i.e. all the nodes in a ring have the same priority level. However, in a WSN, there is usually a sink obtains the global view of the sensing environment and there may exist middle layer cluster heads aggregate or compress data and. Therefore, unbalanced traffic flows from sensor

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nodes to sink nodes or cluster heads are commonly osserved. MAC protocol still has to accommodate unbalanced traffic.

In this study we propose a Two-level Priority Based Wireless Token Ring Protocol (TPWTRP), on the base of WTRP, TPWTRP provide a collision free distributed MAC with two-class priorities delay guarantee, in which nodes claim token in a two-level logical cyclic order, use parallel 1-limited for normal nodes and Exhaustive services for key node (cluster head) to realize the priority-based scheme. By method of imbedded Markov chain theory and generation function, the closed-form expressions for the accurate analysis of the upper key system performance characteristics are achieved.

TPWTRP has advantages as follow: Firstly, on the base of WTRP, it realizes the self-organization; secondly, different service scheme and service route for cluster head and normal node achieve the priority differentiation; thirdly, parallel scheme provides an effective performance in delay guarantee and system stability.

MODEL DESCRIPTION

Assume that the token ring is set up and managed as shown in ref (Ergen *et al*., 2004), consisting of one sink node (or base station) and one key sensor node and a number of common sensor nodes deployed over a geographic area (sensing field). Data are transferred from sensor nodes to the sink through a one-hop communication paradigm and we will not go further on the setup and manage procedure in detail.

In TPWTRP, Each ring has N+1 nodes (Q_1, Q_2,…, Q_h), N normal nodes indexed by i (i = 1, 2, …, N), in which packets are transmitted in parallel 1-limited mechanism and a high priority node (cluster head) by h, in which packets are served in exhaustive scheme.

In the first polling level, token passes between the high priority node Q_h (cluster head) and a normal node Q_i; in the second level, for each time after the Q_h finished packets transmission in an exhaustive service discipline, the N normal nodes are polled in a cyclic order in a parallel 1-limited service discipline.

In TPWTRP, when the token arrives Q_i (i = 1, 2, … N) at time t_n, if the node has packets in storage, the node will process the service, while simultaneously switching to Q_h. Once Q_i finishes the delivery of a limited number of data packets according to the 1-limited service protocol, Q_h begins to transmit at t_n*. After Q_h finishes the transmission according to the exhaustive service scheme, Q_{i+1} acquires token and begins transmitting at t_{n+1}. It is clear to see, in this model, Q_h is a higher-priority node and the rests are lower-priority nodes.

The mathematic model is proposed under the assumption as follow in ref (Zhao and Zhen, 1994).

Define a random variable $\xi_i(n)$ as number of packets in storage at node i at time t_n. Then, the status of the entire ring at time t_n can be represented as $\{\xi_1(n),\ldots,\xi_h(n)\}$. While $\xi_i(n^*)$ is the number of packets in storage at node h at time t_n^* and the status of the entire ring at time t_n^*can be represented as $\{\xi_1(n^*),\ldots,\xi_N(n^*),\xi_h(n^*)\}$. For:

$$\sum_{i=1}^{N}\rho_i+\rho_h<1$$

($\rho_i = \lambda_i\beta_i$, $\rho_h = \lambda_h\beta_h$), we will always assume the nodes are stable.

We set up generation function of the two categorizes nodes as follow.

The generating function for the number of packets present at token arrival instants $t_n^*$is:

$$\begin{aligned}G_{ih}(z_1,z_2,\cdots,z_N,z_h)&=\lim_{n\to\infty}E\left[\prod_{j=1}^{N}z_j^{\xi_j(n^*)}z_h^{\xi_h(n^*)}\right]\\&=R_i\left(A_h(z_h)\prod_{j=1}^{N}A_j(z_j)\right)G_i(z_1,\cdots,z_N,z_h)\Big|_{z_i=0}+\frac{1}{z_i}\\&\quad B_i\left(A_h(z_h)\prod_{j=1}^{N}A_j(z_j)\right)\left[G_i(z_1,\cdots,z_N,z_h)-G_i(z_1,\cdots,z_N,z_h)\Big|_{z_i=0}\right]\end{aligned}\tag{1}$$

where, $G_i(z_1,\ldots,z_i,\ldots,z_N,z_h)$ is the generating function for the number of data packets present at the instants of token arrive at node i.

The generating function for the number of packets present at $t_{n+1}$is:

$$\begin{aligned}G_{i+1}(z_1,\cdots,z_N,z_h)&=\lim_{n\to\infty}E\left[\prod_{j=1}^{N}z_j^{\xi_j(n+1)}z_h^{\xi_h(n+1)}\right]\\&=G_{ih}\left(z_1,\cdots z_N,B_h\left(\prod_{j=1}^{N}A_j(z_j)F_h\left(\prod_{j=1}^{N}A_j(z_j)\right)\right)\right)\end{aligned}\tag{2}$$

PERFORMANCE ANALYSIS

Derivative of generation functions: First order derivative of generation functions: We assume the first derivative of generation functions:

$$g_i(j)=\lim_{z_1,\cdots,z_i,\cdots,z_N,z_h\to1}\frac{\partial G_i}{\partial z_j},\ g_{i0}(j)=\lim_{z_1,\cdots,z_N,z_h\to1}\frac{\partial G_i\big|_{z_i=0}}{\partial z_j}$$

and:

$$g_{ih}(j)=\lim_{z_1,\cdots,z_N,z_h\to1}\frac{\partial G_{ih}}{\partial z_j},\ j=1,\cdots,N,h$$

Take it with Eq.(1) and Eq.(2), we have:

$$1-G_i(1,\cdots,z_i,1,\cdots 1)\Big|_{z_i=0}=\frac{N\lambda\gamma}{1-\rho_h-N\rho+N\lambda\gamma} \tag{3}$$

$$g_{ih}(h)=\frac{\lambda_h\gamma(1-\rho_h)}{1-\rho_h-N\rho+N\lambda\gamma} \tag{4}$$

Second order derivative of generation functions: The second first derivatives of generation functions are defined as:

$$g_i(j,k)=\lim_{z_1,\cdots,z_N,z_h\to 1}\frac{\partial^2 G_i}{\partial z_j\partial z_k},\ g_{i0}(j,k)=\lim_{z_1,\cdots,z_N,z_h\to 1}\frac{\partial^2 G_i\big|_{z_i=0}}{\partial z_j\partial z_k}$$

and:

$$g_{ih}(j,k)=\lim_{z_1,\cdots,z_N,z_h\to 1}\frac{\partial^2 G_{ih}}{\partial z_j\partial z_k}$$

where, $i = 1, 2, ..., N$; $j = 1, 2, \ldots, N, h$; $k = 1, 2, \ldots N, h$. By substituting the second derivative of Eq. 1 and 2, give the expressions of g_{ih} (h, h) and g_i (I):

$$\begin{aligned}g_{ih}(h,h)=&\left[A_h^{'}(1)\beta+\lambda_h^2B^{''}(1)-\lambda_h^2R^{''}(1)-A_h^{''}(1)\gamma\right]\\&\frac{N\lambda\gamma}{1-N\rho-\rho_h+N\lambda\gamma}+\lambda_h^2R^{''}(1)+A_h^{''}(1)\gamma\\&+2\lambda_h(\gamma-\beta)g_{i0}(h)\end{aligned} \tag{5}$$

$$\begin{aligned}g_i(i)=&\frac{1-\rho_h}{2(1-N\rho-\rho_h)}\Bigg\{N\left(\gamma A^{''}(1)+\lambda^2R^{''}(1)\right)+\frac{2N\rho_h}{1-\rho_h}\left(\lambda^2R^{''}(1)+\lambda^2r\right)+\frac{N\rho_h^2}{(1-\rho_h)^2}\left(\gamma A^{''}(1)+\lambda^2R^{''}(1)\right)\\&+\frac{N\lambda}{1-N\rho-\rho_h+N\lambda\gamma}\Bigg[N\gamma(\beta-\gamma)A^{''}(1)-N\lambda^2\gamma R^{''}(1)+\frac{1}{1-\rho_h}\Big(2N\lambda^2\gamma\rho_h(\beta-\gamma)-2N\lambda^2\gamma(1+\rho_h)R^{''}(1)\\&+2\gamma(1-\rho-\rho_h)+\lambda\gamma\rho_h(1+\rho_h)-(N-1)\lambda\gamma^2+2(N-1)\lambda\gamma(\gamma-\beta)\Big)+\frac{\lambda}{(1-\rho_h)^2}\Big(N\lambda\gamma B^{''}(1)\\&-N\lambda\gamma\rho_h^2R^{''}(1)+\gamma\beta_h^2\left(\rho_h+N\lambda(\beta-\gamma)\right)A_h^{''}(1)+\lambda_h\gamma B_h^{''}(1)\Big)\Bigg]\Bigg\}\end{aligned} \tag{6}$$

Delay performance

Average queue length: The mean queue length E (L_i) of node j (j = 1,..., N, h) is defined as the number of data packets in the buffer between two successive arrivals of the token arrive at this node. It is given by E (L_j) = g_i (i) and in like manner E (L_h) = g_{ih} (h).

Mean circular cycle (inter-arrival time): Mean circular cycle C measures the average time between two successive transmissions for a certain sensor node:

$$C=\frac{1-G_i(z_1,\cdots,z_i,\cdots,z_N,z_h)\big|_{z_i=0}}{\lambda}=\frac{N\gamma}{1-\rho_h-N\rho+N\lambda\gamma}$$

Mean waiting time: Mean waiting time is the time from when a packet enters the storage of Q_i to when it is served. Let the generation function of the random variable w_i be W_i. According to (Zhao and Zhen, 1994), in the discrete time system we have mean time for a packet waiting for transmitted is:

$$E(w_1)=\frac{1}{\lambda C}g_i(i)-\frac{1}{\lambda}-\frac{A^{''}(1)}{2\lambda^2}$$

Take with Eq. 11, it is easy to obtain the closed form expression of mean waiting time.

The high-priority packets in node Q_h is served in the exhaustive scheme, under the theory in reference (Zhao and Zhen, 1994), we could get the expression of the average waiting time as follow:

$$w_h=\frac{g_{ih}(h,h)}{2\lambda_h g_{ih}(h)}-\frac{A_h^{'}(1)}{2\lambda_h^2(1+\rho_h)}+\frac{\lambda_h B_h^{''}(1)}{2(1-\rho_h)}$$

THEORETICAL CALCULATION AND SIMULATION

To assess the accuracy of the expression and the efficiency of the TPWTRP, we have performed numerical experiments to test the accuracy of the exception for different values of the workload of the system. Consider a logical ring (cluster) with ten node-one high priority node (cluster head) and nine normal nodes.

In this example we illustrate the accuracy of theoretical analysis and the model performance with superiors in the high priority queue. Table 2 shows the queue length and the mean waiting time for TPWTRP. The analytical results coincide with the simulation results. Workload of the model:

$$G=\sum_{i=1}^{N}\rho_i+\rho_h<1$$

grows with the increasing of the customer arrive rate λ. In both scenarios we fixed up the service time to be 10 slots. The model held 9 nodes which give 5 slots to take care of switching when it is necessary. We can clearly see that with the growth of G, characteristic increasing distinctly in Q_i, from G=0.05 to G=0.9, the mean waiting time grows from 23.330-251.670 slots. While the performances in Q_h

Table 2: Mean waiting time of TPWTRP

	Mean waiting time in Q_i		Mean waiting time in Q_h	
Arrival rate	Theory	Simulation	Theory	Simulation
0. 05	23.3297	23.3201	2.1382	2.1575
0. 2	28.3265	28.3087	2.5612	2.5174
0. 4	38.9097	38.9119	3.1458	3.1555
0. 6	60.1383	60.1272	3.7553	3.7515
0.9	251.6978	251.4791	4.7198	4.7375

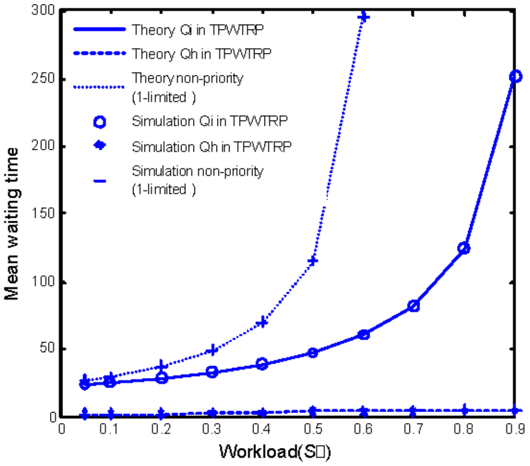

Fig. 1: Comparison with non-priority scheme

are much better, mean waiting time are much lower than normal queues, for instance, when G = 0.05, the mean waiting time is 2.138 slots, about 9.2% of Q_i. Furthermore, the growth in Q_h with G presents much more smoothly. When G = 0.9, its mean waiting time just 4.720 slots.

It is worth considering whether the high priority queue acquires better performance at the expenses of performance degradation in normal queues. In order to answer this question we compare TPWTRP model with non-priority polling models with 1-limited discipline. System models have the same arriving rate, service time and switch over time. We just vary the working mechanism. Overall models contain ten queues.

Figure 1 shows the mean waiting time for different traffic loads for TPWTRP and non-priorities with 1-limited scheme. TPWTRP has smaller delay than 1-limited systems. With the groups of arrival rate in Q_h, server assigns more time to serve it cause of the exhaustive mechanism. So, that Q_h has a stable performance in the entire procedure.

DISCUSSION AND EXTENSIONS

In this study, we proposed a Two-level Parallel Wireless Token Ring Protocol (TPWTRP) for delay sensitive multimedia WSNs. On the base of WTRP, it provides a collision free distributed MAC with two-class priorities delay guarantee. Nodes are provided a priority distinguished service, furthermore high priority-level node acquire more service opportunities in a two-level polling mechanism. We got the closed from expressions of average queue length and mean waiting time, which are exactly coincide with the computer simulation results. As we have show, the protocol fulfills requirements of multi-priority. High level node has a superior performance in queue length and delay, as well as low normal nodes still worked stable.

On the other hand, we have limited ourselves to analysis two-class priorities in this document. However, more priorities levels protocols are worth of study in the future.

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