Multiple Access with Attention-Based Tournaments for Monitoring Over Wireless Networks

Chithrupa Ramesh, Henrik Sandberg, and Karl Henrik Johansson

Abstract— **Wireless sensor networks for control and monitoring applications introduce critical constraints on the design of multiple access schemes. Controlling dynamic processes requires that priority must be given to critical systems for the use of the wireless medium. Tournaments in the medium access control (MAC) layer are presented as a way to evaluate priorities and assign channel resources in a distributed manner. The priorities are dynamically assigned based on the attention that each data packet requires. A mathematical formulation of attention is presented together with the corresponding performance analysis of the multiple access scheme. Priorities based on the attention emphasize the information content in the data to be transmitted and the related process dynamics. It is shown that under certain conditions, the performance of this distributed scheme converges to a scheduling policy based on minimizing the per-sample variance of the error in the estimates obtained with limited communication resources. Sustainable data rates for a cluster of linear processes are also derived.**

I. INTRODUCTION

The design of Medium Access Control (MAC) schemes for wireless sensor networks is a challenging task [1]. These networks are typically characterized by low data rates, high node densities and power constraints [2],[3],[4]. Low packet generation rates, variable packet sizes and time-insensitive, non-critical applications have motivated the design of the IEEE 802.15.4 Hybrid-MAC scheme [5]. This scheme is not well suited to wireless sensor networks for control and estimation applications. While these networks share many of the features of wireless sensor networks in general, they differ primarily due to the delay sensitive, critical nature of the dynamic processes involved. Performance optimization over such networks requires communication infrastructure that meets real-time constraints [6]. Packet losses and delays cause performance deterioration. Also, the packet generation rates are not necessarily low, though packet sizes are small [7].

For sampled systems, an effective multiple access mechanism is Time Division Multiple Access (TDMA). However, such static schedules cause poor channel utilization due to hogging of slots by infrequently sampled processes. Dynamic scheduling requires a centralized scheduler, which does not have access to the measurements to make a valid real-time choice. Other contention-free schemes suffer from the same drawbacks [15]. Contention-based mechanisms such as Slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) ensure minimum delays for low traffic loads. As the traffic load increases, the throughput deteriorates and delays become intolerable. More importantly, these are random access schemes, which do not prioritize transmissions based on the physical processes monitored by the sensors or the information contained in the current measurement [8], [9].

The time-criticality of data requires the introduction of some priority between sensors, while retaining a contention-based architecture. Previous attempts at introducing priorities within CSMA/CA include arbitration inter-frame space or contention window differentiation, such as in IEEE 802.11e. These are probabilistic measures that make it hard to analyze performance [10]. A more certain method of ensuring priority is called for here. In this paper, we introduce a prioritized access scheme with reserved slots, which are won through a tournament. The idea of a tournament to resolve contention based on static priorities is already prevalent in the literature, e.g., the CAN Bus Protocol [11] and its recent adaptation to wireless networks in WiDOM [12]. However, the priority mechanism in our proposal is dynamic, and priorities are assigned to data packets, not to nodes.

The importance of dynamic priority-based multiple access schemes for monitoring over networks can be motivated with a simple example. A chemical process plant has sensors measuring physical phenomena related to the plant process, along with sensors for non-critical applications such as light sensors to automatically turn on or off lights in the building. All these sensors may in future share the same wireless media, and must contend for the channel to transmit their measurements to the processor. A temperature sensor containing critical information could be blocked by the light sensor, if using a random access scheme. Such situations require prioritized access for QoS guarantees to be met. The tournament access protocol presented in this paper is a suitable multiple access method to evaluate packet priorities and assign channel slots.

Static priorities can be assigned to sensors, but this is often inefficient. A fire detector in the chemical plant is likely to be assigned a higher priority than a pressure sensor monitoring operational pressure levels, but the pressure measurements at most time instants are likely to contain more important information regarding operation of the plant as compared to routine (safe) measurements from the fire detectors. Dynamic priorities based on information in the current measurements are hard to assign for heterogenous sensors measuring vastly different physical quantities.

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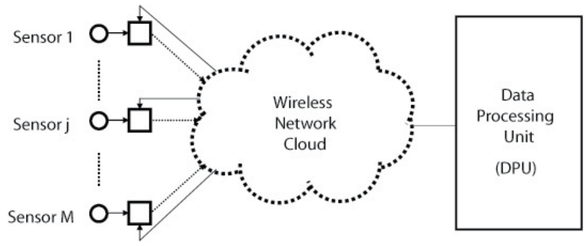

Fig. 1. A typical scenario depicting Monitoring over a Wireless Network, along with the Multiple Access Solution presented in the paper.

This paper presents a method of assigning these dynamic priorities. A node evaluates the criticality of the current measurement to be transmitted to the controller or monitoring unit and assigns an appropriate priority. The priority is a measure of the attention that a packet requires from the controller. A suitable *Attention Factor* is introduced. It ensures that the performance of the multiple access scheme converges to a centralized scheduling policy based on minimizing the per-sample variance of the error in the estimates obtained with limited communication resources. The corresponding throughput and delay analysis of such a Tournament Access Protocol are presented.

The outline of the paper is as follows. Section II formulates the problem. The Attention Factor and the Tournament Access Protocol is given in Section III. Section IV presents the performance analysis of the protocol. Simulation results illustrating the system behaviour is given in Section V. The paper is concluded in Section VI.

II. PROBLEM FORMULATION

Fig. 1 illustrates a network with M sensors, whose measurements are monitored over a wireless network by a data processing unit. We describe next one of the sensors and its underlying process. Each node senses a physical process with state $x \in \mathbb{R}^n$ and communicates the sensor reading $y \in \mathbb{R}^m$. The state and measurements are related by the process model

$$\begin{aligned} x(k+1) &= Ax(k) + w(k) \\ y(k) &= Cx(k) + v(k), \end{aligned} \tag{1}$$

where $A \in \mathbb{R}^{n\times n}$ and $C \in \mathbb{R}^{m\times n}$ are constant matrices. The process noise w and the measurement noise v are zero mean white Gaussian with covariance matrices $Q \in \mathbb{R}^{n\times n}$ and $R \in \mathbb{R}^{m\times m}$, respectively. Each sensor node in the network has its own process model.

The process model is known to both the sensor and the data processing unit. The task of estimation is performed in the sensor node itself as it is assumed to have sufficient processing capability. The estimated state could be used for monitoring, control or detection applications. In this paper, we restrict the applications to logging and alerting, which corresponds to Classes 5 and 4, respectively, in the ISA SP100 Classification [16]. Closed-loop control applications will be investigated in our future work.

Unlike in a point to point network, where every sensor has a dedicated communication channel to the processor, the wireless media is a common shared resource which does not permit simultaneous updates from multiple sensors to the processor. Thus, the network requires a multiple access mechanism that enables sensors to contend for channel resources. As discussed in the introduction, a dynamic priority-based multiple access scheme is most effective for such networks. Tournaments can be used to evaluate dynamic priorities which have been assigned in a distributed manner and arbitrate channel access. This is illustrated in Fig. 1.

The problem addressed in this paper is how to assign dynamic priorities to data packets based on the measurements from the sensors. Each node should evaluate the criticality of its measurement in the context of a heterogenous sensor network, without communicating with its neighbors. The rest of the paper deals with the problem of formulating such a distributed dynamic priority and evaluating the performance of the resulting multiple access scheme.

III. TOURNAMENT ACCESS PROTOCOL

This section discusses the mathematical formulation of the attention factor, which is the dynamic priority assigned by each node to a data packet due for transmission. Optimal properties of this priority measure are derived. Then, a multiple access protocol based on this attention factor is presented.

A. Attention Factor

The Attention Factor (α) is designed to call the attention of the data processing unit to the current data in the network node or its deviation from the last known value (known to the data processing unit) and the penalty in not being able to transmit this packet.

The formulation below is described with respect to the state model of one node in the network. Recall the process model in Equation 1. The network node assigns α to its own data packets. At time $k-1$, the sensor of the network node delivers measurement $y(k-1)$ to its local estimator. With this information, the estimator derives the expected value of x given all measurements up till time $k-1$ denoted $\hat{x}(k-1|k-1)$, which it sends to the data processing unit over the network. This unit can use its knowledge of the corresponding process model to generate the predicted estimates $\hat{x}(k|k-1), \hat{x}(k+1|k-1), \ldots$. The motivation for allocating channel resources to deliver the next packet is the innovation $e(k)$ in the measurement $y(k)$, given by

$$e(k) = y(k) - C\hat{x}(k|k-1). \tag{2}$$

The predicted estimate can then be updated as

$$\hat{x}(k|k) = \hat{x}(k|k-1) + K_f(k)e(k); \tag{3}$$
$$K_f(k) = P(k|k-1)C^T R_e(k)^{-1},\ R_e(k) = CP(k|k-1)C^T + R;$$

where P is the covariance matrix of the error in the predicted state estimate. The risk in not being able to deliver this packet can be evaluated by computing the difference between the predicted estimates $\hat{x}(k+1|k-1)$ and $\hat{x}(k+1|k)$:

$$\hat{x}(k+1|k-1) = A\hat{x}(k|k-1); \quad \hat{x}(k+1|k) = A\hat{x}(k|k). \tag{4}$$

The predicted estimate is used here to further emphasize the process dynamics, making α more sensitive to unstable processes.

We denote the attention associated with the measurement $y(k)$ (or data packet at time k) by $\alpha(k)$. $P_{\text{samp}}\{y(k)\}$ (or $\bar{\alpha}(k)$, which is related to $\alpha(k)$) is the increase in the sample variance of the prediction error due to not receiving a packet at time k, which contains information about $y(k)$ (or $e(k)$). The notation $\bar{\alpha}(k)$ is used in addition to $P_{\text{samp}}\{y(k)\}$ to stress its relation to $\alpha(k)$ or the attention factor.

$$\begin{aligned}\bar{\alpha}(k) = P_{\text{samp}}\{y(k)\} &= \text{tr}\{(\hat{x}(k+1|k) - \hat{x}(k+1|k-1)) \\ &\times (\hat{x}(k+1|k) - \hat{x}(k+1|k-1))^T\}; \quad (5)\end{aligned}$$

where $\text{tr}\{\cdot\}$ is the trace operator. $P_{\text{samp}}\{y(k)\}$ is an empirical quantity based on knowledge of the measurement $y(k)$. The expected value of $\bar{\alpha}(k)$ is then proportional to the increase in the variance of the prediction error at the data processing unit due to not possessing information about the measurement $y(k)$:

$$\begin{aligned}E_k[\bar{\alpha}(k)] &= \text{tr}\{AK_f(k)E[e(k)e^T(k)]K_f^T(k)A^T\} \\ &= \text{tr}\{P(k+1|k-1) - P(k+1|k)\}. \qquad (6)\end{aligned}$$

Applying this concept of attention as the dynamic priority used by data packets in the network to gain channel access, we can derive an interesting property: $\eta_j(k)$ defines the ratio of $P_{\text{samp}}\{y(k)\}$ of the j^{th} node to $E_k[P_{\text{sys}}\{\mathbf{y}(k)\}]$, i.e.,

$$\eta_j(k) = \frac{P_{\text{samp},j}\{y(k)\}}{E_k[P_{\text{sys}}\{\mathbf{y}(k)\}]}; \; P_{\text{sys}}\{\mathbf{y}(k)\} = \sum_{j=1}^{M} P_{\text{samp},j}\{y(k)\}; \quad (7)$$

where $P_{\text{sys}}\{\mathbf{y}(k)\}$ is the net increase in the prediction error variance due to not possessing information about measurements $\mathbf{y}(k)$ from all the nodes in the network at time k. In a prioritized access scheme, the channel is allotted to the data packet which maximizes $\eta_j(k)$. Then,

$$\max_j \, E_k \eta_j(k) = \max_j \, \frac{\text{tr}\{P_j(k+1|k-1) - P_j(k+1|k)\}}{\sum_j \text{tr}\{P_j(k+1|k-1) - P_j(k+1|k)\}}; \quad (8)$$

states that the data packet (measurement) which results in maximum reduction of the prediction error variance at the estimator is most likely to be allotted channel access. Thus, priorities based on $\bar{\alpha}$ minimize the net error variance of the estimates, which is equivalent to an optimal (per sample) scheduling strategy given limited communication resources.

B. Tournament Access Protocol

Now that dynamic priorities have been assigned to the data packets, there remains the task of designing an arbitration policy to resolve contention. In other words, how should the data packets exchange priorities and decide who gets to transmit. The tournament access protocol (TAP) solves this problem.

The frame structure of the tournament access period is presented in Fig. 2. There are N_{TAP} tournament slots in each period, and sensors that wish to transmit in this frame must generate an Attention Factor (α) as described in Section III-A. The formulation for $\bar{\alpha}$ in Equation 5 is scaled and rounded to a fixed length notation for α:

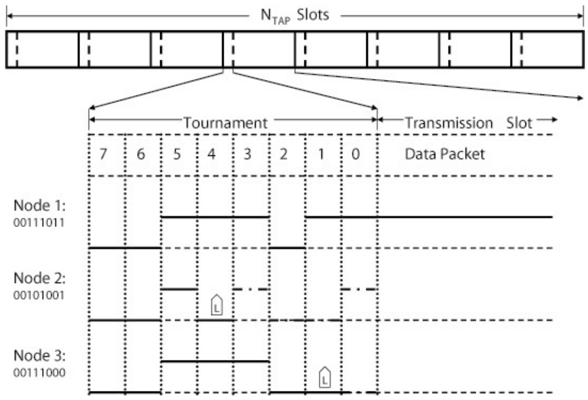

Fig. 2. The Frame Structure of the Tournament Access Protocol. An example of a tournament is depicted below, where 'L' indicates that the node has lost the tournament.

$$\begin{aligned}&\alpha(k) = \text{round}\left(\text{tr}\{AK_f(k)e(k)e^T(k)K_f^T(k)A^T\} \cdot \frac{A_{\max}}{P_{\text{smax}}}\right); \\ &P_{\text{smax}} = \text{tr}\{KK_f(k)R_e(k)K_f(k)K\}. \qquad (9)\end{aligned}$$

The discussion in Section III-A is unaffected by this modification for sufficiently large values of $A_{\max}$, which is the largest value of attention. Here, P_{smax} can be thought to be the maximum tolerable increase in the sample variance of the prediction error due to not possessing information about a measurement from a node attached to a process with identity system matrix ($A = I$). This emphasizes the attention values for dynamic processes. K is a positive integer with which each process dictates its own tolerance limits and influences the increase of α with deviating measurements.

A tournament precedes every transmission slot in the TAP. During the tournament, qualifying packets transmit their Attentions, starting with the most significant bit. Nodes transmit a suitably chosen pulse for a bit of value one and remain silent during the zero bit. As wireless transceivers cannot transmit and receive at the same instant, nodes can listen during the zero bits. A busy channel indicates that they have lost the tournament. The packet(s) with the most number of ones in the attention factor wins the tournament. As the attention factors are assigned by each node, more than one packet can have the same attention factor and win the tournament. Multiple winners are not aware of each other, and cause a collision. Using the same mechanism as in CSMA/CA, nodes are aware of a collision by the lack of an acknowledgment (ACK). Fig. 2 illustrates the concept of a tournament between three nodes with attentions 59, 41 and 56 respectively. Nodes 2 and 3 lose the tournament after transmitting 4 and 7 bits of their priorities, as they hear a busy channel during their recessive bits. Node 1 wins the tournament and transmits in the succeeding slot.

IV. PERFORMANCE ANALYSIS

The performance of a multiple access scheme is characterized by its throughput and delay. However, in the case of TAP, the probability of transmission conditioned on the attention factor is an important parameter. This computation requires a probability distribution for the attention factor, which is given by

$$p(A_F = \alpha) = \qquad (10)$$
$$\begin{cases} \phi(0.5 \cdot \frac{P_{\text{smax}}}{A_{\max}\sigma^2}) & \text{if } \alpha = 0; \\ \phi((\alpha+0.5) \cdot \frac{P_{\text{smax}}}{A_{\max}\sigma^2}) - & \\ \phi((\alpha-0.5) \cdot \frac{P_{\text{smax}}}{A_{\max}\sigma^2}) & \text{if } 0 < \alpha < A_{\max}; \\ 1 - \phi((A_{\max}-0.5) \cdot \frac{P_{\text{smax}}}{A_{\max}\sigma^2}) & \text{if } \alpha = A_{\max}; \end{cases}$$

where, $\phi(x)$ is the cumulative distribution function of the Chi Squared distribution. The sum of unnormalized squared Gaussian variables ($\text{tr}\{AK_f ee^T K_f^T A^T\}$) with unequal variances has a multivariate Gamma-type distribution [13]. However, for process models with $m = 1$ ($e \in \mathbb{R}$), $\text{tr}\{AK_f ee^T K_f^T A^T\} \sim \sigma^2\chi_1^2$, where χ_1^2 represents the Chi-squared distribution with one degree of freedom and σ^2 is the variance of the scalar term. If the variances of the innovation vector components are equal, then again, $\text{tr}\{AK_f ee^T K_f^T A^T\} \sim \sigma^2\chi_m^2$, where m is the number of measurements in the process model. A motivation for reducing m is that higher order Chi-squared distributions tend towards a normal distribution, increasing the probability of collisions. This is explained in detail in Section V.

The performance analysis is performed with respect to the average probability density of the attention variables of all the nodes participating in the tournament, which is referred to henceforth as $p_{AF}(\alpha)$. This is given by

$$p_{AF}(\alpha) = \frac{1}{M}\sum_{j=1}^{M} p_j(A_F = \alpha); \quad \text{for } 0 \le \alpha \le A_{\max} \qquad (11)$$

where M is the number of nodes, each of which are assumed to have a packet to transmit.

In any tournament slot, a packet can lose the tournament, or win the tournament. After winning the tournament, a packet can collide with another, or succeed in transmission. To derive the probabilities of these events, we define quantities p_L, p_{LE}, p_G in

$$p_L = p(L|\acute{\alpha}) = p(\alpha < \acute{\alpha});\ p(\alpha < \acute{\alpha}) = \sum_{\alpha<\acute{\alpha}} p_{AF}(\alpha)$$
$$p_{\text{LE}} = p(LE|\acute{\alpha}) = p(\alpha \le \acute{\alpha});$$
$$p_G = p(G|\acute{\alpha}) = p(\alpha > \acute{\alpha}) = 1 - p(\text{LE}|\acute{\alpha}); \qquad (12)$$

These quantities refer to the conditional probability of another packet with attention less than (p_L), less than or equal to (p_{LE}) and greater than (p_G) a given value $\acute{\alpha}$.

Now, we arrive at the conditional probability (conditioned on the attention α) of winning a tournament in N slots against $M-1$ other packets, as given in

$$p(W_{N,M-1}|\alpha) = \sum_{n=0}^{N-1} C_n^{M-1} p_{\text{LE}}^{M-1-n} p_G^n; \qquad (13)$$

where $C_k^n = \frac{n!}{(n-k)!k!}$ refers to the binomial coefficient. This equation states that there can be only up to $N-1$ packets with attentions greater than any value $\acute{\alpha} \in \alpha$ and that the rest must have attentions less than or equal to $\acute{\alpha}$. There can be more than $N-1$ packets with attentions greater than $\acute{\alpha}$, but these additional packets must have equal attentions and collide. To simplify the analysis, we assume that the probability of collisions in previous slots is negligible. This assumption is valid for correct choice of the parameter $A_{\max}$, as shown in Section V. Also, a design of TAP based on this assumption increases the throughput.

The conditional probability of losing tournaments in all N slots against $M-1$ packets is then given by

$$p(L_{N,M-1}|\alpha) = 1 - p(W_{N,M-1}|\alpha); \qquad (14)$$

The conditional probability of succeeding in transmission in N slots against $M-1$ packets is given in

$$p(Tx_{N,M-1}|\alpha) = \sum_{n=0}^{N-1} C_n^{M-1} p_L^{M-1-n} p_G^n \qquad (15)$$

which differs from Equation 13 by requiring that the other packets have attentions strictly less than any value $\acute{\alpha} \in \alpha$. Finally, the conditional probability of a collision under these circumstances is given by

$$p(C_{N,M-1}|\alpha) = p(W_{N,M-1}|\alpha) - p(Tx_{N,M-1}|\alpha). \qquad (16)$$

The probability of successfully transmitting a packet in N_{TAP} slots against $M-1$ other packets is obtained by setting $N = N_{\text{TAP}}$ in Equation 15. We can then define an attention specific throughput as given by

$$S_{\text{TAP}}(\alpha) = \frac{p(Tx_{N,M-1}|\alpha)p_{AF}(\alpha)Len(P)}{T_{\text{TAP}}}; \qquad (17)$$

where $Len(P)$ is the packet payload size and T_{TAP} is the length of the Tournament Access Period (TAP). The attention specific throughput is a more useful parameter as it is a direct indicator of the performance of our prioritized MAC scheme. Packets with different attention factors (or priorities) view the medium as a channel with throughput $S_{\text{TAP}}(\alpha)$, where α is the attention of the packet. Averaged over $p_{AF}(\alpha)$, the mean throughput (S_{TAP}) is given by

$$S_{\text{TAP}} = \sum_{A=0}^{A_{\max}} S_{\text{TAP}}(\alpha) \approx \frac{N_{\text{TAP}} \cdot Len(P)}{T_{\text{TAP}}}. \qquad (18)$$

For $M > N_{\text{TAP}}$ and a negligible probability of collision, this can be expressed more simply as shown.

We define the average conditional delay ($E[d|\alpha]$) in terms of the number of frames by which the packet has been delayed, as given in

$$E[d|\alpha] = 1 \cdot p_1(Tx|\alpha) + 2 \cdot (1 - p(Tx|\alpha_1))p(Tx|\alpha_2); \quad (19)$$

$p(Tx|\alpha_d)$ refers to $p(Tx_{N,M-1}|\alpha(k+d))$ from Equation 15 for $N = N_{\text{TAP}}$ slots in the d^{th} frame after the packet was generated. Higher order terms are neglected, as the probability of their occurring is designed to be small. The attention factor as a function of delay is given by the term $\alpha(k+d)$, where

$$\bar{\alpha}(k+d) = tr\{AK_f(k+d)e(k+d)e^T(k+d)K_f^T(k+d)A^T\}.$$

The above analysis has assumed M nodes with a packet each in every frame. A more realistic scenario would be to consider M nodes with average packet generation rates $\{\lambda_m\}$. Then,

$$M\bar{\lambda} \leq N_{\text{TAP}}; \text{ where, } \bar{\lambda} = \frac{\sum_{m=0}^{M} \lambda_m}{M}; \qquad (20)$$

provides a limit on the average rate ($\bar{\lambda}$) for a cluster of linear processes, where N_{TAP} is the number of packets that this Medium Access Control Layer can support per frame.

V. SIMULATION RESULTS

In this section, we simulate TAP in Matlab and present results that give us an insight into how the attention factor varies with system dynamics and delays. These results also provide a validation of our analysis.

A. Results

Consider a network with $M = 20$ nodes. Each node generates a packet to transmit, and these packets vie for $N_{\text{TAP}} = 10$ tournament slots. The maximum value that the attention can take is $A_{\max} = 255$, which is sufficiently large to prevent frequent collisions while maximizing throughput.

The parameter K, referred to in Equation 9, can be set to 5, which is sufficient to produce a decaying probability distribution curve, as shown in Fig. 3a. Lower values of K result in a peak at the higher end of p_{AF} (defined in Equation 11), and higher values of K under utilize the range of p_{AF}. Critical nodes must set a lower K to generate packets with high attention values for small deviations in the measurements.

In these simulations, we consider models with a single state variable and measurement ($n = 1, m = 1$ in Equation 1). Fig. 3b illustrates the variation in the probability distribution of the attention factor for process models with different dynamics. Stable processes ($A = 0.5$) probabilistically generate lower values of attentions than unstable processes ($A = 2$).

Fig. 3c illustrates the variation in the probability distribution of the attention factor with delays. Note that a delayed packet is more likely to generate a higher attention factor.

Thus, the attention factor satisfies the basic requirements of a dynamic priority based on measurements.

Next, the tournament access period was simulated in Matlab. A homogenous network was considered for simplicity, with model parameter $A = 1$. The attention factor was generated in the same frame as the data packet ($d = 1$). The results matched the analysis closely, as shown in Figs. 4 and 5. The conditional probability of winning, transmission and losing are close to the analytical values because the probability of a collision is negligibly small for high values of α.

The conditional probabilities of winning and transmission are almost 1 for packets with high attentions. The peak in the conditional probability of collision (Fig. 5) can be explained from the probability density function of α. $p_{AF}(\alpha)$ indicates that there are few packets with large attentions. These are most likely to win the tournament in the first few slots and transmit without collision. Hence, the curve falls to nearly 0 for high values of α. Packets with lower values of α mostly win the tournament in the last few slots, and since there are many such packets, collisions are very likely. Finally, the packets with very low values of attention do not win the tournament often, and hence the probability of collision is low for these values.

B. Discussion

We can now make some inferences from these results, which could help us improve the design of TAP.

We would like to design TAP such that $p(Tx_{N_{\text{TAP}},M-1}|\alpha) \approx 1$ and $p(C_{N_{\text{TAP}},M-1}|\alpha) \approx 0$, for higher values of attentions. To ensure these properties hold, it is essential that the probability distribution of α tapers away consistently. If the curve were more bell-shaped, for instance, the probability of collision would be higher for the mid-range values of α as there would be more packets with these values.

From Fig. 5, it is clear that the throughput of TAP will be significantly affected due to a large number of collisions in the final few slots. This can be treated as a design constraint and the number of slots (N_{TAP}) chosen to be fewer than the number of packets with attentions greater than a value $A_{\min}$. $A_{\min}$ should be chosen from Fig. 5, such that for $\alpha > A_{\min}, p(C_{N,M-1}|\alpha) \approx 0$.

But, this does not solve the problem, since a well designed $p_{AF}(\alpha)$ will ensure that most packets in the network have low values of attentions. These packets should clearly not use the tournament, but must still be given a chance to contend for the channel. These packets would be better off using a contention access scheme such as Slotted CSMA/CA, since their priorities are nearly equal. Thus, TAP is well suited for a hybrid Medium Access Control along with Slotted CSMA/CA. The tournament slots are simply reserved slots for packets with higher priorities.

Finally, since only packets with α greater than $A_{\min}$ are to use the tournament slots, it could be effective to scale the attentions within the range ($R : A_{\min} \leq \alpha \leq A_{\max}$) over the entire range of α ($0 \leq \alpha_R \leq A_{\max}$). Here, α_R is the new scaled attention within the range R. This translation retains the order of priorities in α, but uniformly spreads each value over a number of values in the new scale α_R. Now, the probability of another packet with the same priority (α_R) is lowered, which reduces the probability of a collision and increases the throughput of TAP.

VI. CONCLUSIONS

This paper considers the problem of identifying multiple access schemes for monitoring over networks. We have presented a dynamic priority formulation called the Attention Factor, as well as an arbitration mechanism that uses this priority. The Attention Factor is set by the node for each packet based on the current measurement value. The formulation permits a relative prioritization of heterogenous sensor measurements. This formulation also minimizes the net per-sample variance of the estimates obtained with communication constraints. Finally, a performance analysis for this

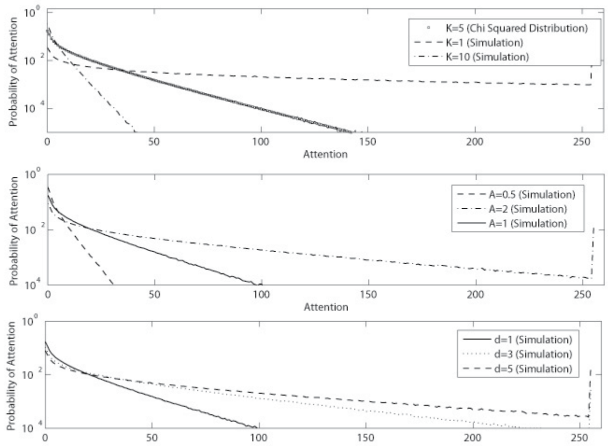

Fig. 3. This figure shows the probability distribution of the attention factor (a) for different values of K, (b) for processes with different dynamics (different A) and (c) with delay (d).

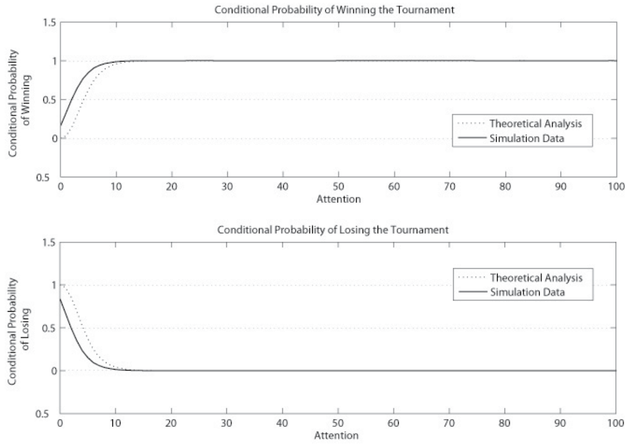

Fig. 4. This figure shows the conditional probabilities of winning and losing in TAP. Note that the simulated data matches the analytical values.

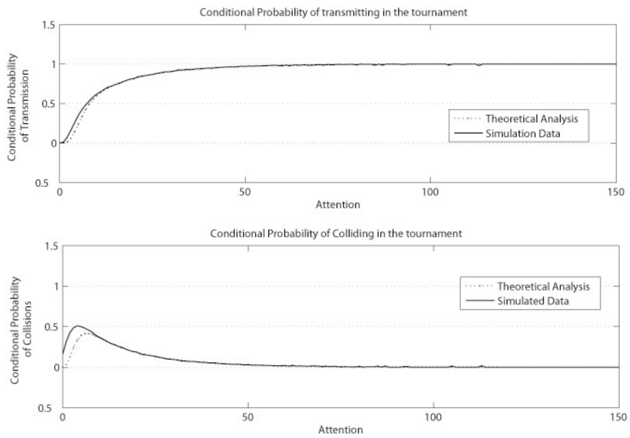

Fig. 5. Conditional Probabilities of Transmission and Collision in TAP. The conditional probability of collision shows a peak at low values of attention, which indicates that TAP is not well suited for this range of attentions. TAP could be used along with Slotted CSMA/CA in a Hybrid MAC, with the tournament slots reserved for packets with higher attentions.

multiple access scheme was presented along with simulation results. Future work includes implementing the proposed TAP in our wireless sensor and actuator test bed.

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