Design of a Distributed Protocol for Proportional Fairness in Wireless Body Area Networks

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Abstract—We study a distributed protocol for time-division multiple access (TDMA) with applications in wireless body area networks. Our scheme is derived from a bio-inspired algorithm known as Pulse-Coupled Oscillator, in which each node in the network update its state based on its knowledge of the neighborhood. The protocol we propose is suitable for negotiation of a shared resource in a distributed manner, and is adaptive to changes in the network size or in the nodes’ demands. We discuss the implementation of such scheme from an application perspective, and discuss the impact of the physical layer on its performance.

I. INTRODUCTION

In wireless body area networks (WBANs), a cluster of nodes sample biological signals of the human body and communicate to them an access point. As observed by several Authors (see e.g. [1]), the specifications of Zigbee [2], Bluetooth [3], Mica Motes [4] and other commercial platforms in WBAN applications are, in fact, CSMA-like schemes, suitable in applications where nodes are intermittent, i.e., bursty traffic. Although in WBANs the sensor activity is very different for different classes of sensors, the sources rates are quite regular. Another important aspect of WBAN, is the need of curtailing the energy consumption via aggressive duty-cycling of the radios. Most of the standards cited above attain that through the energy consumption match closely the actual source activity.

Our idea is that of regulating all the activities of the network, including the physical layer, targeting a desired emergent behavior, with simple, scalable, local rules that regulate the transmission and reception patterns of each node in a decentralized fashion. Building on the bio-inspired PCO primitive proposed in [5] for UWB transmission, we consider the UWB ON-OFF PCO radio design in [6] as our canvas, and complete it with the necessary primitives for access and two way communications with the access point of the WBAN. Once again, to give scalable designs, we propose to harmonize active and inactive transmission and reception times across the network with very simple dynamics inspired by nature.

Main Contribution: Compared to our previous work in [7], what this paper contains is a holistic design of a PCO-UWB ad hoc network system for WBAN that can potentially lead to a micro-watts ad-hoc network. The goal of this paper is to endow the radio with the suite of primitives that regulates the access of the nodes and their receiver activity, as well as to provide channel state information for the transmitter and receiver adaptation. We provide a novel ad-hoc network MAC primitive that, by combining our scheme for proportional fairness proposed in [7] and the PCO protocol, allows to aggressively duty-cycle the nodes transmissions and reception. The final objective is to control at the lowest level (the level of bit) when the node is active and inactive, so as to have the energy consumption match closely the actual source activity.

II. PCO FOR GLOBAL SYNCHRONY

Pulse coupled oscillators (PCOs) are elements that pulse periodically (every firing cycle \( T_{PCO} \)) if isolated, but may alter their pulsing patterns in response to the signals heard from other elements if interconnected (hence the adjective “coupled”). The evolution of the local time at node \( i \) is characterized by a phase variable

\[
\Phi_i(t) = \left( \frac{t}{T_{PCO}} + \phi_i \right) \mod 1, \tag{1}
\]

which is a real-valued variable that increases linearly from 0 to 1 in each cycle. When the phase \( \Phi_i(t) \) reaches 1, node \( i \) emits a pulse and reset its phase back to 0. When the nodes are interconnected, the reception of a pulse at any given node alters its phase. Specifically, if node \( i \) receives a pulse at time \( t \), it will immediately update its local phase variable at time \( t^+ \) as

\[
\Phi_i(t^+) = f^{-1}(f(\Phi_i(t)) + \varepsilon) \tag{2}
\]

where \( f(\cdot) \) is a smooth, monotonically increasing and concave-down function, and the parameter \( \varepsilon > 0 \) is called coupling strength. As we can see, the recipient of a pulse will move earlier or later its own firing by altering a local clock that regulates the pulse emission of the node. We can pictorially show the phases of all nodes representing them as dots moving on a circle of unitary length (normalized period) with constant speed. Their phase is their position on the circle, and the firing event (a node emits a pulse) takes place whenever a node crosses the finish line. By following simple local coupling rules, networks of PCOs are known to produce a variety of pulsing patterns, which have been used to model the spiking...
of neurons in the brain or the flashing of fireflies. Under mild conditions on the choice of the dynamics \(f(\cdot)\) it has been shown that synchronous state is reached almost surely [8].

A. PCO Radio Experiments

Preliminary experimental results on the implementation of the PCO protocol were obtained on commercial hardware platforms [9], [10]. More recently, an ad-hoc hardware platform with synchronous state is reached almost surely [8].

The PCO clock gives synchronization at the bit level, providing a great advantage to the access layer. In fact, the nodes can interpret the PCO beats as giving the margin of a tape where they can write or read their bits, by activating one of the bins available in each PCO frame. Note that global synchrony is achieved without exchange of explicit information among the nodes, so it happens before any other network infrastructure is set in place. Our problem is to structure the writing and reading of the channel, delimited by the PCO global clock, with very simple primitives.

III. BIO-INSPIRED MAC LAYER

In [7] we proposed a bio-inspired proportional fair scheduling (PFS) scheme inspired by the PCO protocol, that we will refer to as the PFS-PCO MAC. Even in PFS-PCO MAC we have clocks associated to nodes; the difference is that, in our case, each node has two clocks, namely, \(\Phi_{1,i}(t)\) and \(\Phi_{1,2}(t)\), where \(i\) is the node index. As before, these clocks may be thought as dots moving clockwise over the unitary circle at the same speed, as shown in Figure 1.

We assume that all nodes are interconnected through direct transmission links and that each of them has a demand \(K_i \in [1, K_{\text{max}}]\) that indicates its request, where \(K_{\text{max}}\) is a design parameter known to all nodes. \(K_i/K_{\text{max}}\) can be thought as the portion of shared resource node \(i\) is hoping to obtain; in our particular case, the resource shared by the nodes is the circle of unitary length, and the request vector is defined as \(K = (K_1, K_2, \ldots, K_n)\).

The updating mechanism works as follows. Suppose that clock 1 of node \(i - 1\) crosses the finish line at time \(t\), i.e., \(\Phi_{1,i-1}(t) = 0\). Node \(i\) updates its two state variables \(\Phi_{1,i}(t)\) and \(\Phi_{1,2}(t)\) as follows:

\[
\begin{align*}
\Phi_{1,i}(t^+) &= \gamma \Phi_{1,i}(t) + (1-\gamma)\Phi_{\text{target}}(t) \\
\Phi_{1,2}(t^+) &= \gamma \Phi_{1,2}(t) + (1-\gamma)\Phi_{\text{target}}(t)
\end{align*}
\]

where \(\gamma \in (0,1)\) and

\[
\begin{align*}
\Phi_{\text{target}} &= \frac{\delta}{K_{\text{total}} + \delta} \Phi_{i+1,2}(t) \\
\Phi_{\text{target}} &= \frac{\delta}{K_{\text{total}} + \delta} \Phi_{i+1,2}(t)
\end{align*}
\]

with \(\delta > 0\). The following theorem establishes the convergence properties of the algorithm defined by (3)-(III).

**Theorem 1:** [PROPORTIONAL FAIRNESS [7]] The algorithm in (3) converges for all initial conditions \((\Phi_{1,1}, \Phi_{1,2}, \ldots, \Phi_{n})\), except over a set of measure zero. Furthermore, by letting \(\Gamma_i(t) = \Phi_{1,i}(t) - \Phi_{1,2}(t)\) (mod 1), and \(\Theta_i(t) = \Phi_{1,2}(t) - \Phi_{1,i-1}(t)\) (mod 1), we have

\[
\lim_{t \to \infty} \Gamma_i(t) = \frac{K_i}{K} \quad \text{and} \quad \lim_{t \to \infty} \Theta_i(t) = \frac{\delta}{K},
\]

for all \(i\), where \(\delta = \frac{1}{1+\frac{\phi}{K}}\) and \(K = \sum_{i=1}^{n} K_i\).

As we mentioned before, the order of nodes’ clocks needs to be preserved so that the nodes can transmit without collisions in the interval gap between their own firing events. This allows to use the bandwidth as the schedule is computed and it has also the benefit of making unnecessary to identify explicitly the node that it is firing. Thus, we need to avoid the overlapping of intervals that are between the two firing events of different nodes. To ensure that this constraint is met at all times, one can modify the update equations as follows:

\[
\begin{align*}
\Phi_{1,i} &= \gamma \max(\Phi_{\text{target}}, \Phi_{1,i} - \Phi_{1,2}) + (1-\gamma)\Phi_{1,i} \\
\Phi_{1,2} &= \gamma \min(\Phi_{\text{target}}, (\Phi_{1,2} + \Phi_{1,i} - \Phi_{1,2})/2) + (1-\gamma)\Phi_{1,2}
\end{align*}
\]

From the result of Theorem 1 we can see that the amount of time a node obtains by negotiation with the others converges to a quantity proportional to its demands, \(K_i\). In particular, if the shared resource is time and the unitary circle is the period, node \(i\) earns an interval of time equal to \(\kappa K_i\). Thus, the ratios are preserved since the quantities obtained by two different nodes \(i\) and \(j\) are \(\kappa K_i\) and \(\kappa K_j\) and, thus, \(\kappa K_i/\kappa K_j = K_i/K_j\).

\[1\] We finally observe that the total amount shared by the nodes sums up to \(\kappa T_{\text{PF}}\), meaning that the remaining time equal to \(1-\kappa\) or \(\kappa T_{\text{PF}}\) is divided into empty spots useful to accommodate new nodes. The factor \(\kappa/K\) determines the “loss” of resource due to absence of a central controller, or access point, responsible for assigning

\[1\] Notice that this policy is inherently different from other scheduling mechanisms such as Max-Min fairness [11] where, instead, the scheduling guarantees a sufficient amount of resource to nodes with limited demand and provides best effort for the remaining users.
to each node its corresponding time share. \( \kappa \) is, therefore, a number that quantifies how our algorithm for distributed TDMA is performing with respect to centralized TDMA.

IV. DESIGN AND IMPLEMENTATION

Although in principle the algorithms work correctly, it is not possible in practice to have variables with infinite precision: this is not only due to the fact that they are stored into a buffer, but also to the fact that the any pulse has positive duration in time.

A. Quantized Proportional Fairness

We can imagine a quantized version of the algorithm described in III. The two clocks count time in terms of numbers of PCO frames (of duration equal to \( T_{PCO} \)), so they effectively indicate at what PCO frame node \( i \) wants to start transmitting and at what PCO frame node \( i \) has ended its transmission. Thus, the PCO hardware platform developed in [6] can be used to achieve this task. The unit step of our scheme for proportional fairness is equal to the PCO period \( T_{PCO} = 7 \mu s \). Consequently, the period of the algorithm described in Section III is \( T_{PF} = LT_{PCO} \), where \( L \) is a parameter indicating the number of frames used to form a period. Assume that at time \( t \) node \( i \) updates its two clocks using (3). In order to make the state independent of the quantization noise, the new clock values will be quantized as

\[
\hat{\Phi}_{i,1}(t) \triangleq \min_j \left| jL - (\Phi_{i,1}(t) + v) \right|
\]

\[
\hat{\Phi}_{i,2}(t) \triangleq \min_j \left| jL - (\Phi_{i,2}(t) + u) \right|
\]

in analogy with the quantized consensus-type update with dithering studied in [12], where \( u \) and \( v \) are uniform r.v.s with support on \([-2L^{-1}, 2L^{-1}]\).

B. Implementation

Algorithm 1 shows the pseudo-code of a direct implementation of the PFS-PCO algorithm in an event-driven fashion, where each node utilizes the time between its own clock to transmit data to the access point. The events that need to be handled are the reception of a beacon signals and the end of the period. In the first case the node records its distance to the neighbors; in particular the beacon heard right before the local firing will be the distance to the preceding neighbor, while the first firing after the two local ones will be used to update the clock values.

This algorithm can also work for a system architecture with an access point (AP). So, instead of each node being forced to seek its downlink information, wasting time in reception. The AP will utilize a fixed portion of PCO-frame period (downlink) of duration \( T_{PCO} \) with the purpose of echoing the activities of the nodes (beginning and end of transmissions), while the rest of the period is utilized by the node currently under transmission (uplink). This mechanism makes the overall algorithm more robust to channel non-idealities letting the nodes to exploit, more safely, a new feature: energy saving.

Each node could, in fact, keep its radio on for an amount of time sufficiently large to hear the clocks of its phase neighbors, and shut the transceiver off for the rest of the period.

C. Parameters Choice

We propose two ways of implementing the choice of \( K_i \) at the local level:

- **preference model**: each node is given a preference hard-coded in its memory, based on its priority that depends on what the sensor will be monitoring, that is, if sensor \( i \) has priority over sensor \( j \) then \( K_i > K_j \);

- **rate constrained model**: each node has a minimum number of bits to transmit per period, that we indicate with \( d_i(t) \). The current allocation, in terms of number of bits per frame assigned to node \( i \), is indicated by \( \lambda_i(t) \). If such number of bits is not at least equal to \( d_i(t) \), the node increases its demands, embedded in \( K_i \), keeping in mind that \( K_i(t) \leq K_{max} \). Therefore, in the rate constrained model, the update of parameter \( K_i \) is given by

\[
K_i[m + 1] = \max \left\{ [K_i[m] + \text{sgn}(\lambda_i[m] - d_i[m]) - K_{\text{max}}]_+, 1 \right\}
\]

where \( \text{sgn}(\cdot) \) is the sign function and \( m \) is a multiple integer of \( T_{PF} \).\(^3\)

Missed detections and false alarms introduce errors in the algorithm, since the update is based on clock firings implemented through the transmission of signals within the bins corresponding to state variables \( \Phi_i \) and \( \Psi_i \). If not properly handled, the algorithm may not be working correctly. If the coupling strength is fairly small, having an incorrect estimate of the neighbors’ states does not hurt significantly the algorithm, because the node only makes small phase jumps in each iteration.

\[^2\]In the context of WBANs, this quantity is approximately constant.

\[^3\]Note the analogy between (6) and the distributed implementation of CSMA with back-pressure [13].

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Algorithm 1 Event-driven description of our proportional fairness scheme.

1. **Receive Beacon**:
   2. if (enabled)
   3. record(i+1, t); enabled = false;
   4. [start, stop] = update();
   5. set_start_clock();
   6. else
   7. record(i-1, t);
   8. endif
9. **start clock Tick**:
10. begin_TX;
11. set_stop_clock();
12. **stop clock Tick**:
13. stop_TX; enabled = true;

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V. IMPACT OF THE PHYSICAL LAYER

The transmission of clock signals corresponds to the transmission of specific beacons in the portion of PCO frame allotted to the sensors, encoding the start and end signals. In this section we describe the physical layer model of the UWB radio and show how to design the receiver for the beacons and extract information about the channel state.

A. Channel Model

We consider a scenario where $K$ sensors are wearable by a patient and sending their radio signals to an (AP) in a hospital room. A recent contribution of the IEEE 802.15.6, the task group for BAN, describes a channel model for UWB transmission in a hospital room environment [14]. The model involves multipath effects. However, the received power of the second path is around 22 dB below the strongest path. Therefore, we focus on the first received path and neglect multipath [14]. The channel is then given by:

$$h(t) = \sqrt{G}e^{j\phi}G(t - \tau)$$

where

$$G = \Omega e^{-\frac{\tau}{S}}$$

The channel parameters are defined as:

- $h(t)$: complex channel impulse response.
- $G$: signal power associated with strongest path.
- $\phi$ is the associated phase which is uniformly distributed $[0, 2\pi]$.
- $\tau$ is the path arrival time modeled as a Poisson random variable, with arrival rate $1/0.5/125$ nsec.
- $\Omega$ is the path loss. Free space path loss model is assumed for the system under study and is given by

$$\Omega = G_t G_r \left( \frac{c}{4\pi df_s} \right)^2$$

where $G_t$ and $G_r$ are the gains of the transmit and receive antennas, respectively, $c$ is the speed of light, $d$ is the distance between the receive and transmit antennas, and $f_s$ is the carrier frequency. $f_s = 4.5$ GHz for the system model in this paper.

- $\Gamma$ is the decay rate of the power delay profile.
- $S$ is the shadowing effect and is modeled as a log-normal shadowing random variable, $S \sim \text{lognormal}(0, \sigma_s^2)$, where $\sigma_s$ is the standard deviation in dB.

B. System Model and Signaling Parameters

The PCO synchronization mechanism supports the channel access technique and the subdivision of the spectrum because it allows to precisely duty cycle the radio to turn on and off the transmitter and receiver in the dedicated spots of the frame. We assume that the nodes synchronization errors are a small percentage of the bin and include the effect of asynchronism in our fading model. Let us assume that each bin has a normalized duration of one, so that in the $n = iB + b$ bin we have the $b^{th}$ bin of the $i^{th}$ frame. More specifically, the transmit a bandpass pulse is a waveform $g(t) = \Re\{p(t)e^{j2\pi f_o t}\}$ where the envelope $p(t)$ meets the FCC mask requirements. If the channel delay $\tau$ is modest, denoting by $\sqrt{G}$ the channel amplitude gain, the reception of an on-off signal transmitted in bin $n$ corresponds to the reception of:

$$r(t) = \Re\{\sqrt{G}x_n p(t - n - \tau)e^{j2\pi f_o (t-n-\tau)}\} + w(t)$$

where $x_n = 0$ (OFF) or $x_n = 1$ (ON). The term $w(t)$ denotes the thermal noise whose two-sided power spectral density is given by $N_o$. As well known, the model above can also capture well the scattering that has delay spread that is negligible, i.e. whose coherence bandwidth is larger than the bandwidth of the complex envelope $p(t)$. Start and end beacons are used to mark the data portion of each user so that no confusion between no transmission and a “zero” bit transmission is established.

Due to the low complexity requirements, the receiver is non-coherent [15]. To avoid the fading effects one should extract the absolute value square of the projection onto the signal space. Considering, without loss of generality, the signal centered in bin 0, to extract the statistics, the receiver projection consists of the projection onto the filters $p(t)\cos(2\pi f_o t)$ and $-p(t)\sin(2\pi f_o t)$ followed by the calculation of the absolute value square, i.e.:

$$\hat{r} = \int p(t)e^{-j2\pi f_o t}r(t)dt = |\sqrt{G}e^{j\phi}E_p x + w|^2,$$

where $w \sim CN(0, E_p, N_o/2)$. We define the decision made at the receiver as $y = 1(\hat{r} > \xi)$, where $1(\cdot)$ is the unit-step function and $\xi$ the decision threshold.

C. Threshold Choice

Assuming the channel gain $G$ is known, then using the complex Gaussian model, all is needed for the threshold choice is to derive the likelihood function $f(\hat{r}|x, G)$ and what results from this assumption is that the conditional distributions $f(\hat{r}|1, G)$, $f(\hat{r}|0, G)$ are non central and central $\chi$-square respectively. The threshold that minimizes the error probability is the one given by the Maximum A Posteriori (MAP) rule and can be derived to yield.

$$\exp \left( -\frac{G}{2N_o/E_p} \right) \int \left\{ \sqrt{G\hat{r}/(N_o/E_p)} \right\} \geq 1$$

In practice the receiver receives from different nodes on different bins and it does not know $G_i$ for the nodes so using the optimum threshold is not possible. Hence, the performance of the MAP detector is simply a theoretical bound. The question is how to set the threshold for the detection of the symbols in some reasonable way that ensures coverage of the sensors of interest. The details of which, together with capacity analysis and error correction coding discussion appears in [16].

Given a threshold $\xi$, one can model the channel as a binary memoryless channel with input $X$ and output $Y$ where the
transition probabilities are
\[ \alpha \triangleq P(Y = 0|X = 0) = \int_0^\xi f(\hat{r}|0)d\hat{r} \]
\[ = 1 - \exp \left( -\frac{\xi}{2N_o/E_p} \right) \]  \hspace{1cm} \text{(11)}
\[ \beta \triangleq P(Y = 1|X = 1) = \int_\xi^{+\infty} f(\hat{r}|G, 1)d\hat{r} \]
\[ = Q_1\left( \sqrt{\frac{G}{N_o/E_p}} \sqrt{\frac{\xi}{N_o/E_p}} \right) \]  \hspace{1cm} \text{(12)}
where \(Q_1(.)\) is the generalized Marcum’s Q-function.

At any range \(\alpha\) does not change, but \(\beta\) does, so \(\beta\) is a function of the transmitter receiver channel, a fact that we will highlight by including a suffix \(\beta_i\) to denote the transmitter. For transmitters that are further away from the receiver \(\beta_i\) will be reduced while it will tend to one as they get very close. The probability of error of the receiver when node \(i\) transmits is given by:
\[ P_e(i) = \frac{1}{2}(1 - \alpha) + \frac{1}{2}(1 - \beta_i) = 1 - \frac{\alpha}{2} \left( 1 + \frac{\beta_i}{\alpha} \right). \]  \hspace{1cm} \text{(13)}

D. The Detection of the Start and End Beacons

To implement our Multiple Access Control (MAC) protocol, given \(\{y_n\}_{n=1}^N\), we need to distinguish between the following four hypotheses: 1) \(H_s\): the input is a start beacon \(\{s_n\}_{n=1}^N\); 2) \(H_e\): the input is an end beacon \(\{e_n\}_{n=1}^N\); 3) \(H_o\): the input are i.i.d. data; 4) \(H_b\): the input is all zeros. The following Lemma summarizes the receiver identification of the beacon sequences.

Lemma 1: The optimal decision for the hypothesis \(H_i\) is obtained by choosing \(H_i\) for which \(\Lambda(\{y_n\}_{n=1}^N|H_i)\) is maximum, where \(\Lambda(\{y_n\}_{n=1}^N|H_i)\) is equal to
\[ \sum_{n=1}^N \left[ g(x_n, y_n)(y_n x_n \log \beta + \bar{y}_n x_n \log \alpha) ight. \]
\[ + g(x_n, y_n)(\bar{y}_n x_n \log(1 - \beta) + y_n x_n \log(1 - \alpha)) \] \hspace{1cm} \text{for} \ H_s, H_e, H_o \text{ \ where } g(x, y) \text{ is the ex-or function. Moreover,}
\[ \hat{\beta} = \left( \left( \sum_{n=1}^N y_n x_n - \sum_{n=1}^N \bar{y}_n x_n \right) \left( \sum_{n=1}^N y_n x_n \right)^{-1} \right)^+ \]
while for \(H_b\) we have \(\Lambda(\{y_n\}_{n=1}^N|H_b) = \log \frac{p}{1 - p} \sum_{n=1}^N y_n + N \log(1 - p)\) where \(p = \frac{\beta + 1 - \alpha}{2}\) and \(\hat{\beta} = \left( \alpha - 1 + \frac{2 \sum_{n=1}^N \bar{y}_n}{N} \right)^+\).

Proof: Please refer to [16].

\(\beta\) is found by resorting to a generalized likelihood ratio test (GLRT), that requires maximizing the likelihood of each hypothesis with respect to the unknown parameter \(\beta\). This provides a way of implementing the algorithm in hardware with simple detection rules and without the need for training to estimate the physical layer parameters.

VI. NUMERICAL RESULTS

In Figure 2 we report an example with \(n = 5\) nodes, with requests vector \(K = [5, 5, 1, 1, 5]\) and 256 frames per period \(T_{PF} = 256 T_{PCO}\). The horizontal axis is the iteration index, while the vertical axis represent the amount of period obtained by the nodes. In this case, the coupling parameter is \(\gamma = 0.03\) (small jumps), \(K_{\max} = 5\) and \(\delta = 2\). The probabilities of missed detection and false alarms are \(P_m = 10^{-3}\) and \(P_f = 10^{-4}\). We can see that the state of the network is quickly established, and the nodes obtain an amount of time proportional to their demands. Occasionally, some spikes occur because either missed detections or false alarms cause the nodes to get incorrect estimates of their neighbors state. The empty spots are about 0.08 (21 frames) as forecasted by the theoretical results. In the same figure is also reported the evolution of the system under idealistic conditions (in grey), i.e., with no quantization and no errors due to channel noise.

In Figure 3 we allow the nodes to leave and join the network. Within the first 500 iterations, 5 nodes are present in the network with \(K = [4, 4, 1, 1, 1]\). At iteration 500 a new node, node 6 joins the network with demand \(K_{6} = 1\). At iteration 1000, 2 nodes leave the network (nodes 3 and 6) and the request vector becomes \(K = [4, 4, 1, 1]\). We can see that, in all cases, the network reaches a new equilibrium corresponding to the ratios of the nodes’ demands.

In Figure 4 are reported the probabilities of false alarm and missed detection based on the detection rule we discussed above, as a function of the beacon length. In order to include the effects of noise and fading we set \(\alpha = 0.9\), while \(\beta\) is uniformly distributed in \([0.75, 0.9]\) and estimated using the GLRT. The start beacon codeword consists of the first half bits equal to one and the remaining equal to zero (and its complement is used as end beacon). We can see that for reasonable values of the beacon length, such probabilities are
The probability of missed detection / false alarm corresponds to the amount of time obtained by the node. For the algorithm to converge with small values of $K$, the parameter $\kappa_T$ of nodes in the network, the parameter of uniformly distributed $\alpha \in [0.75, 0.9]$, and estimated using the GLRT.

In Figure 5 we report the ratio of the frame period $T_{PF}$ utilized by the nodes, i.e., $\frac{\alpha T_{PF}}{K}$ as a function of the number of nodes in the network, the parameter $\delta$, two values of $K = \{3, 5\}$ and random vector $\mathbf{K}$. As expected as either $\delta$ or $n$ increase, the portion of time utilized for data transmission decreases. In particular we can see that $\frac{\alpha T_{PF}}{K}$ decreases significantly as $\delta$ increases for a small number of nodes meaning that the sustainable number of nodes is limited and the probabilities of missed detection and false alarm must be limited in order for the algorithm to converge with small values of $\delta$. However, when $n$ is large, changes in $\delta$ have little effect on $\frac{\alpha T_{PF}}{K}$.

VII. CONCLUSIONS

In this paper we discussed a protocol for proportional fairness, with application in wireless body area networks. This model is inspired by the Pulse-Coupled Oscillator, and makes use of signals at the physical layer to adjust the nodes’ clocks in a way that is proportional to their demands. We discussed the implementation of such protocol at the application layer and studied the impact of the non-idealities at the physical layer. Our results show that this scheme represents a potential MAC protocol alternative for body area networks.

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