Adaptive Time Slots Control in Wireless Sensor Networks for Delay-aware Applications

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Abstract—Wireless Sensor Networks (WSNs) have been proposed for various monitoring applications including environmental, industrial, military and health care. The use of WSNs with cluster-tree topologies for such applications solves the limited coverage issue of the wireless sensor devices and allows them to be deployed in wider area. WSNs with cluster-tree topologies suffer from various problems including accurate synchronization of beacons used in the beacon enabled mode in the IEEE 802.15.4 standard and providing Quality of Service (QoS) to delay-aware applications. In this paper, we present a Time Slot Control (TSC) scheme that can adaptively manage the allocation of time slots in the beacon enabled mode of operation to provide QoS guarantees to delay critical traffic. Our proposed scheme can improve the end-to-end delay and throughput of selected traffic types by managing the time slots between sensor devices in an optimum way.

Index Terms—IEEE 802.15.4, WSNs, Cluster-tree topology, Time slot, End-to-end delay, Throughput, delay-aware applications.

I. INTRODUCTION

Due to strict delay and reliability requirements, many industrial, security and medical monitoring applications use sensors that are hard-wired to the monitored and controlled environments. Some examples are sensors that monitor a patient’s vital signals or hard-wired accelerometers that monitor a structure or a machine. Although the use of wired sensor systems can provide less delay and higher throughput. Monitoring via hard-wired sensors is proven to be costly, require constant maintenance, it is unscalable, restrict system mobility and in some situations very difficult to control. To mitigate these problems in some monitoring applications, Radio Frequency (RF) has been used to transmit sensed data from the sensor to the sink. The problem with using an individual, unnetworked system is that it does not easily and flexibly provide the user with the correlation between the measured values. The development of the IEEE 802.15.4 standard [1] for Low-Rate Wireless Personal Area Networks (LR-WPANs) has enabled the Wireless Sensor Networks (WSNs) to be utilized as one of the emerging technologies that integrate sensing, computing and wireless networking into a single small, low-power, low-cost and self-configured system.

In the early phases of WSN-based monitoring systems such as large scale environmental monitoring, due to the long time span of the monitoring applications and routine measurement of data, reducing the power consumption, for instance by improving the medium access techniques or routing protocols has been the major focus. However, the emergence of new WSNs applications such as the smart grid, Intelligent Transportation System (ITS), homeland security and the actual deployment of the Body Area Network (BAN) requires that these WSNs satisfy certain bounds or requirements on latency and reliability. These delay and reliability requirements are considered vital to the success of the entire monitoring process. Furthermore, certain Quality of Service (QoS) guarantees or differentiation are required to ensure that the occurrence of high priority data is to be delivered to the destination with minimum delay and packet loss ratio. Hence, providing QoS guarantees to the sensor networks with limited resources is one of the critical challenges that needs to be addressed for delay-aware applications.

In WSN with cluster-tree topology, the network comprises of multiple Cluster Heads (CHs) connecting sensor nodes at different levels to the sink node through multi-hop routing. Cluster-tree topologies are used to extend the transmission range of the sensor device especially in wide geographical areas. One of the medium access methods in WSNs with cluster-tree topology is the use of time slot allocation (i.e Time Division Multiple Access (TDMA)). Time slots are allocated via the coordinator node to allow the sensor devices to communicate with each other without packet collision. One of the main issue in such scenarios is accurate synchronisation and coordination of time slots. Therefore, time slots are considered one of the key variables that control the performance of cluster-tree networks and hence can contribute to improving the QoS framework in delay-aware applications.

In this paper, we present a Time Slot Control (TSC) scheme that can adaptively manage the allocation of time slots in the beacon enabled mode of operation to provide QoS guarantees to delay critical traffic. Our proposed scheme can improve the end-to-end delay and throughput of selected traffic types by managing time slot between sensor devices in an optimum way. The TSC scheme builds on the mathematical model of [2] and presents a QoS-aware time slot allocation for a multi-hop cluster-tree topology by optimizing the Guaranteed Time Slots (GTSs) and sleep-wake duration of all sensor devices to minimize the delay and maximize the throughput.

The remainder of this paper is organized as follows. In Section II, we present the related work. In Section III, we present the scenario description and model assumptions, in Section IV we describe the TSC scheme. In section V we present the results and the analysis. Finally, Section VI concludes this work.
II. RELATED WORK

Channel access techniques in cluster-tree based WSNs have been discussed in numerous studies. These studies discuss the timing and scheduling of cluster-tree WSN topologies [3]–[7]. Some of this work assume that sensor device use the timing of the GTS to achieve delay-aware operation framework. This is done by either allowing all sensor nodes in the network to use TDMA or scheduling between CHs and end devices. In our scheme we allow CHs to use a more flexible timing technique for which not only the delay is reduced but also the throughput is increased by adding an other tuning factor between the active and the inactive period of the superframe structure.

The use of tuning of network parameters to achieve optimum operating conditions in WSNs with cluster tree topologies has been studied in the literature [8]–[10]. With the majority of the work discuss the optimization of routing [11], network life time [12] and optimum sensor positions in the network [9].

In [6], the authors have presented an optimization scheme that can achieve low latency while maintaining high reliability values. This is done by allowing CHs to choose optimum packet arrival values to enforce the nodes with low priority to use averaging to reduce their transmission rates. The use of this technique slightly impacts the reliability of packet transmission. In this paper, we overcome this problem by adding another tuning factor in the CHs to increase the throughput of delay-aware transmission as well as decreasing their end-to-end delay.

In [8], the authors have proposed an approach to schedule the superframes of a beacon enabled IEEE 802.15.4 networks with cluster-tree topology by using multiple channels to avoid beacon frame collisions as well as GTS collisions between multiple clusters. This technique requires the addition of a new channel to avoid collision and hence requires modification in the hardware and in the physical layer of sensor devices. We perform the data differentiation for delay-aware transmission by utilizing minimum modifications to the IEEE 802.15.4 standard and by allowing CHs to optimize their MAC parameters to minimize the delay and maximize the throughput.

III. SCENARIO DESCRIPTION AND MODEL ASSUMPTIONS

A. An overview of the IEEE 802.15.4 superframe structure

The format of the optional superframe structure used in the Wireless Personal Area Networks (WPAN) is defined by the WPAN coordinator (PC). According to the IEEE 802.15.4 standard [1], two beacons bound the superframe, this interval is divided into 16 equally sized slots. To deactivate the optional superframe operation, the PC does not transmit any beacons. The superframe is divided onto two segments, namely, active and inactive as shown in Fig. 1. During the inactive segment nodes in a single Personal Area Network (PAN) do not communicate with each and hence enter into a sleep mode to save power. The active segment is divided into Contention Access Period (CAP) and Contention Free Period (CFP). During the CAP devices within the same PAN contend to acquire channel access by using a slotted CSMA/CA mechanism. Additionally, the CFP period is divided into GTSs which appear after the CAP. According to the IEEE 802.15.4 standard, the PC may allocate up to 7 GTSs. However, a GTS can extend to more than 1 slot period.

Different segments of the superframe are described by the values of macBeaconOrder (BO) and macSuperFrameOrder (SO) which are defined in the IEEE 802.15.4 standard. The Beacon interval (BI) can be found using the following relation \( BI = \text{aBaseSuperFrameDuration} \times 2^{BO} \), and the superframe is ignored if the BO is equal to 15. The Superframe Duration (SD) can be found using the following relation \( SD = \text{aBaseSuperFrameDuration} \times 2^{SO} \). If the value of SO is equal to 15, then the superframe should be in inactive mode after the beacon period.

B. Scenario description

We propose to use the TSC scheme in WSNs with cluster-tree topology. A WSN with cluster-tree topology consists of CHs and end device. The CHs have sensing and packets relaying capabilities which are also known as Full Function Devices (FFDs). On the other hand, end devices also known as Reduced Function Devices (RFDs) sense the environment and transmit their packets to a CH. We define a Sub-PAN (SPAN) as a PAN consisting of a number of RFDs connected to a single CH. Multiple CHs connect through each other to form a tree of certain depth and branches as shown in Fig. 2. To achieve synchronisation and to avoid packet collision between these CHs, they generate periodic beacon frames so that each interfering CHs are scheduled during the inactive period of their neighbours. This scheduling is vital in the TSC scheme, since the loss of synchronisation between neighbouring CHs can lead to beacon frames collisions either with other beacon frames or with packets transmitted from different CHs. These collisions lead to loss of synchronization between CHs, resulting in the disconnection of the CHs from the network.

To achieve optimum scheduling between neighbouring CHs, we propose that all CHs in the network communicate with each other using the GTSs in the CFP. We utilize the beacon frame collision avoidance technique described in [3], where beacons are scheduled during the inactive period of the neighbour CHs. The scheduling is done by selecting a specific BO and SO [4], [3] and [5]. Therefore, the TSC scheduling mechanism
In general WSN-based monitoring applications, traffic flow is from sensor device to the sink node. Therefore, in our scenario, we assume that traffic from the sink to the end nodes is mostly for beacon exchange and acknowledgements. Based on this assumption, the effects of opposite direction traffic on the network performance are not significant and can be neglected.

C. Model Assumption

To develop the TSC scheme we follow these assumptions;

- Packets arrive at the MAC sub-layer with an arrival rate of \( \lambda \) packets per second (pkts/s).
- The arrival rate is the same for all RFDs in the network.
- The traffic received by a CH in an upper level \((r+1)\) is equal to the aggregate of traffic from neighbouring CHs at lower levels \(r\).
- All CHs have M/G/1/L queues with a buffer size of \(B\).
- The buffers of CHs can accommodate all of the incoming traffic from their RFDs and neighbouring CHs.
- CHs use the mathematical model described in [2] to estimate the end-to-end delay, the power consumption and the reliability.
- The run time of the mathematical model is negligible and does not affect the end-to-end delay calculations.

IV. THE TSC SCHEME

A. Time Slot Optimization Model

Based on the assumptions made in the previous section, if a CH increases the CAP, it expects to receive more packets from its local nodes (i.e. RFDs). On the other hand, if it increases the CFP it expects to receive more packets form one or more lower level CH. In addition to that, a CH with longer SD is expected to receive more packets from the RFDs and CHs. However, if a specific CH receives more packets from an RFD, a CH or both, it will have to buffer these packets for a duration longer than a single BI which leads to extensive delays. Therefore, a CH must balance between how much data it can receive and how much it can forward to the next level CH within the same BI. In our scheme, we let CHs perform this balance and provide QoS differentiation to high priority traffic. This process is achieved when CHs run time slot optimization to minimize the delay and maximize the throughput for given time slot allocation limitations.

In [2], we proposed a Markov chain-based model to model the behaviour of the IEEE 802.15.4 MAC protocol in single and multi-hop WSNs. In this paper we use the model to allow CHs to estimate the end-to-end delay \((D)\), the reliability \((R)\) and the power consumption \((P)\). We briefly describe \(P, R\) and \(D\) models for cluster tree topology. Further details of these derivations can be found in [2].

1) Power Consumption: Following [2] and [13], we compute the average power consumed in transmitting a packet in a single PAN by summing the average power consumed during backoff \((P_{bo})\), channel sensing \((P_{sc})\), packet transmission \((P_{t})\), idle state \((P_{Q})\), buffering \((P_{B})\), and wake-up \((P_{W})\). Hence, the power consumed in transmitting a packet from an RFD to its CH is given by:

\[
P = P_{bo} + P_{SC} + P_{t} + P_{Q} + P_{B} + P_{W}
\]

(1)

Each of the terms in equation (1) can be computed by knowing the probability of being at a certain state and the amount of average power consumed at that state. For example, if the node consumes an average power of \(p_{bo}\) during backoff, then:

\[
P_{bo} = p_{bo} \left( \sum_{i=0}^{m} \sum_{k=0}^{W_{i}-1} \sum_{j=0}^{n} b_{i,k,j} \right)
\]

(2)

Where, \(b_{i,k,j}\) is the stationary distribution of the Markov chain and is given in [2]. \(W_{0}\) is the smallest backoff window, \(m\) is the maxMaxCSMABackoffs and \(n\) is maxMaxFrameRetries [1]. Note that in equation (1), since each transmitted packet should be followed by receiving an ACK, the power consumed during that process is considered to be a part of \(P_{t}\).

2) Reliability: We define the reliability \((R)\) as the probability of successful packet reception. In slotted CSMA/CA, packets are discarded due to: channel access failure \((P_{cf})\) which takes place when a packet fails to obtain idle channel in two consecutive Clear Channel Assessments (CCAs) within \(m+1\) backoffs, or due to transmission failure \((P_{tx})\), which occurs because of repeated collisions after \((n+1)\) attempts. Based on that, the reliability can be found as follows:

\[
R = 1 - P_{cf} - P_{tx}
\]

(3)

In this paper, we eliminate cumbersome calculations and approximation. The final value of \(R\) can be given by the following equation:

\[
R \approx 1 - x^{m+1}(1 + \tilde{y}) - \tilde{y}^{n+1}
\]

(4)

where, \(\tilde{y}\) is the approximated version of \(y\) and is given by:

\[
\tilde{y} = (1 - (1 - \tilde{r})^{N-1})(1 - x^{2})
\]

(5)

where,

\[
x = \alpha + (1 - \alpha)\beta
\]

(6)

and \(\tilde{r}\) is the approximated version of \(r\) and is given by:

\[
\tilde{r} = (1 + x)(1 + \tilde{y})b_{0,0,0}
\]

(7)
where, \( N \) is the number of nodes in each PAN, \( \alpha \) is the probability that the first Clear Channel Assessments (CCA1) is busy and \( \beta \) is the probability that CCA2 is busy. \( R \) can be seen as a function of the busy channel probabilities \( \alpha \) and \( \beta \), the collision probability \( P_c \) and other MAC parameters [2].

3) End-to-End Delay: We define the average end-to-end delay for a successful packet transmission from an RFD to a CH as the duration from the instant the packet reaches the head of MAC layer queue until an ACK from the CH is received. If a packet is dropped due to either reaching the maximum of backoff limits or the maximum retry limits, its delay is not included into the average delay. Similar to [2], the end-to-end delay (\( D_{PAN} \)) is resulting from the time spent in backoff (\( D_{bo} \)), the time wasted due to experiencing \( j \) collisions (\( jL_C \)), and the time needed to successfully transmit a packet (\( L_S \)).

According to [2] and [13], the average end-to-end delay within a single PAN (i.e. from an RFD to a CH) is given by:

\[
D_{PAN} = L_S + jL_C + D_{bo} = (1 + j)L + D_{bo}
\]  
(8)

where

\[
L_S = L + t_{ack} + L_{ack} + IFS
\]  
(9)

and

\[
L_C = L + t_{ack}
\]  
(10)

where, \( L \) is the packet length and \( t_{ack} \) is the ACK transmission time. In equation 8, because approximate model is used, \( L_S \) is assumed equal to \( L_C \).

To extend the end-to-end delay calculation presented in equation 8 to the entire topology presented in Fig. 2 (i.e. beyond a single PAN), we consider the calculation of the delay at each CH from the tagged RFD to the sink. We let \( \theta_r \) be the occupancy of the CH buffer (\( B_r \)), \( \mu_r \) be the number of packets arriving to \( B_r \) from RFDs and \( \rho_r \) be the number of the forwarded packets from lower level CHs. Therefore, we get:

\[
\theta_r = \mu_r + \rho_r
\]  
(11)

We let \( \gamma_r \) and \( \pi_r \) be the maximum number of data packets that can be transmitted and received from and to a relaying CH during a single SF duration respectively. The values of \( \gamma_r \) and \( \pi_r \) depend on the packet length and the CFP length. By following the same procedure in [2], the single hop delay between CHs \( D_{CH} \) (in time slots) is given by:

\[
D_{CH} = \delta SD + \gamma_r
\]  
(12)

where, \( \delta \) is the number of full superframes a packet is expected to wait in a CH before it is forwarded to an upper CH. Similar to [2], we find \( \delta \) by the following equation:

\[
\delta = \left\lceil \frac{\theta_r}{\gamma_r} \right\rceil - 1
\]  
(13)

Finally, the average single hop delay of all the packets incoming to \( B_r \) (\( D_s \)) is given by the following equation:

\[
D_s = \sum_{n=1}^{\theta_r} \left( \left\lceil \frac{\mu_r}{\pi_r} \right\rceil - 1 \right) D_n + \gamma_r
\]  
(14)

As in [2], a special case is considered where the CH is the sink, in this case, \( D_{CH} \) of the tagged packet in time slot is:

\[
\tilde{D}_{CH} = \delta D_s + \phi
\]  
(15)

where, \( \phi \) represents the number of data packets serviced in the same SF of the tagged packet. Finally, the average single hop delay of all the packets incoming to \( B_r \) (\( D_s \)) in the last hop is given by the following equation:

\[
\tilde{D}_s = \sum_{n=1}^{\theta_r} \left( \left\lceil \frac{\mu_r}{\pi_r} \right\rceil - 1 \right) D_n + \left[ n - \left( \left\lceil \frac{\mu_r}{\pi_r} \right\rceil - 1 \right) \gamma_r \right] \rho_r
\]  
(16)

To find the total end-to-end delay \( D \) from a specific RFD to the sink, we use equations (8) and (16) depending on the number of hops from the tagged RFD to the sink.

We define \( \Omega \) as the ratio of CFP to SD and \( \Psi \) as the ratio of SD to BI. By closely examining the power consumption, reliability and delay presented above, we see that there is a close relationship between \( \Omega \), \( \Psi \) and the variables used in deriving the reliability, the end-to-end delay and the power consumption. Therefore, we base our optimization model on the tuning of \( \Omega \) and \( \Psi \) to achieve highest throughput, minimum delay and power consumption values.

Our aim in this paper is to minimize the end-to-end delay for traffic types requiring certain QoS guarantees. We run the optimization model using Lingo optimization software [14]. We minimize the delay between CHs (i.e. inter-CH delays) for different \( \Omega \) and \( \Psi \) values. The bounds of \( \Omega \) obey the limitations on the maximum number of allowed GTSs defined in the IEEE 802.15.4 standard [1]. Furthermore, the bounds of \( \Psi \) follow typical BO ranges defined in [1]. In addition to that, we set limits for the reliability to be between 95% and 99%. We also maximize the throughput for different \( \Omega \) and \( \Psi \) values and let each CH take an independent decision based on these optimizations. As an example, we set the limits for the delay to be equal to the maximum delay bounds defined in [15].

B. The TSC Algorithm

All CHs running the TSC algorithm estimate the value of the reliability using equation (4) and the delay using equations (8) and (16) during the initial PAN establishment phase. Therefore, all of the CHs will have an approximate value of the expected delay and reliability necessary for running the optimization for different \( \Omega \) and \( \Psi \) values. When a specific CH (we refer to it as the tagged CH) receives a packet tagged with high priority from its own RFDs (we refer to it as the tagged RFD), it finds optimum values of \( \Omega \) and \( \Psi \) that minimizes the end-to-end delay and maximizes throughput levels for the tagged RFD. The tagged CH then broadcasts the optimum values of \( \Omega \) and \( \Psi \) to all of its neighboring CHs. When these CHs receive the optimized \( \Omega \) and \( \Psi \) values, they adjust their own time slots to allow the QoS transmission to go through. Furthermore, to increase the probability of the tagged RFD in accessing the channel and transmitting before other less priority nodes, the tagged RFD runs the DRX scheme [16].
Algorithm 1 TSC Algorithm in the CHs.

//Initialize the MAC variable//
NB ← 0, CW ← 2, BE ← macMinBE
N ← Number of nodes, λ ← Traffic arrival rate
E[R] //Run (R) estimation//
E[D] //Run (D) estimation//
if PRY flag from RFD then
    Optimize Ψ_RFD
    Optimize Ω_RFD
    Broadcast Ψ_RFD & Ω_RFD → CHs
else
    if PRY flag from CH then
        Optimize Ψ_CH
        Optimize Ω_CH
        Broadcast Ψ_CH & Ω_CH → CHs & RFDs
    end if
    else
        if PRY flag from CH & RFD then
            Optimize Ψ_Ch & Ψ_RFD
            Optimize Ω_Ch & Omega_RFD
            Broadcast Ψ_Ch & Ω_Ch & Ψ_RFD & Ω_RFD → CHs & RFDs
        end if
    end if
end if

(IEEE 802.15.4 CSMA-CA Algorithm)

In the DRX scheme the tagged RFD performs CCA in 64 µs instead of 128 µs.

Similarly when the tagged CH receives a packet tagged with high priority from one of its neighbouring CHs, it optimizes Ω and Ψ for that CH and broadcasts Ω and Ψ values to its neighbouring CHs and the RFDs in its PAN. All of the nodes receiving this broadcast (except the one generating the high priority transmission) adjust there time slots based on the received Ω and Ψ values. Furthermore, if the tagged CH receives packets tagged with high priority from a neighbouring CH and its own RFD at the same time, it runs the time slot optimization for the two sources and broadcast the new Ω and Ψ to all nodes. Algorithm 1 describes the TSC algorithm run in each CH.

V. RESULTS AND ANALYSIS

We use QualNet [17] to simulate a WSN with cluster-tree topology. We use a scenario similar to the scenario presented in Fig. 2, we vary the number of nodes in each PAN and the traffic arrival rate (λ) to investigate the performance of the TSC scheme. We compare our results with the default settings of the IEEE 802.15.4 standard and the scheme described in [18], were the node having high priority data performs single CCA with frame tailoring. We refer to the scheme of [18] as (SCCA) in our results. To avoid the hidden terminal problem, we place all RFDs in a single PAN in such a way so that they can hear each other. We activate the acknowledgement mechanism in the network to improve the reliability of the system. We run each simulation for 500 seconds and repeat each simulation 10 times. We set the simulation parameters according to the IEEE 802.15.4 standard document [1] and the actual specification document of MicaZ platform. We set the transmission power to 3.5 dBm, the noise factor to 10 dB and the antenna gain to 0 dBi. Furthermore, we set the contention window to 2 and the packet size to 120 B. In all of the simulations, we consider ideal clocks, compensation of clock drift in sensor devices is out of the scope of this paper.

To find the optimum inter-CH delay (i.e. the delay between CHs) and investigate the optimum time slot allocation, we use LINGO optimization software. Fig. 3 shows the minimum inter-CH delay for different packet arrival rates. We show that as the allocated GTSs increase the inter-CH delay decreases for all λ values. This delay reduction takes place since most of the packets arriving at the tagged CH are serviced and forwarded to the next CH in the same BI. However increasing the number of allocated GTSs decreases the amount of data packets received from the local PAN (i.e. from RFDs) and hence increasing their delay and reducing their throughput. Therefore, at this point the TSC algorithm should control this process according to the source of the high priority traffic.

Fig. 4 shows the average end-to-end delay from the tagged RFD located two hops away from the sink. We show that when the default IEEE 802.15.4 standard is used the delay increases by an amount equal to approximately a single SD every time the packet travels through higher level CHs. The SCCA scheme, exhibits similar behaviour at every hop since the scheme is not designed to handle high traffic in cluster-tree topologies. Finally, the TSC scheme achieves the desired delay reduction for all λ values. This is done through optimizing the time slots at the tagged CH. We show that the simulation results of the TSC scheme agree with the analytical model results.

Fig. 5 shows the throughput of the tagged RFD when the TSC scheme, the SCCA scheme and the IEEE 802.15.4 standard are used. We show that when the tagged RFD (same location as in Fig. 4) implements the TSC scheme the node throughput increases significantly. This increase is due to the optimization of the SD for every λ value. Simulation results show a good agreement with the analytical results. We show that there is no noticeable improvement to the throughput when the SCCA scheme is used.

Fig. 6 shows the average power consumption when the different schemes are used. We show that there is a slight increase in the power consumption when the TSC scheme is used compared to the IEEE 802.15.4 standard and SCCA scheme. This increase is justified since there is an increase in the transmission rate due to the implemented QoS scheme.

VI. CONCLUSION

The use of the IEEE 802.15.4-based Wireless Sensor Network (WSN) systems to monitor delay-aware applications offers many advantages and is expected to be widely implemented in broad range environments. In the beacon enabled mode of operation of the IEEE 802.15.4 standard, careful and deliberate allocation of time slots to sensor devices has a significant impact on the performance of the entire network.

In this paper, we presented a Time Slot Control (TSC) scheme to adaptively optimize the allocation of time slots in cluster-tree topologies so that a certain degree of Quality of Service (QoS) differentiation is granted to delay-aware traffic.
All Cluster Heads (CHs) in a cluster-tree topology run the TSC scheme by carefully tuning the Contention Access Period (CAP), Contention Free Period (CFP) and the Superframe Duration (SD) to minimize the end-to-end delay and maximize the throughput of sensor nodes that are transmitting delay critical traffic. Simulation and analytical results showed that our TSC scheme could significantly reduce the end-to-end delay and increasing the throughput while maintaining acceptable power consumption values.

As a future work, we intend to study the effects of asynchronous clocks and consider the compensation of clock drift in sensor devices.

REFERENCES

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