CUSTOMIZED MAC PROTOCOL FOR SMALL PROPERTIES WITH WIRELESS IRRIGATION AUTOMATION

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Abstract— DyTEE (Dynamic Timed Energy Efficient) is a collision-free data medium access control (MAC) protocol for wireless sensor and actuator networks (WSAN) designed for building and rural automation environments. The new protocol was implemented on Zigbit Atmel platform modules and then compared to standard IEEE 805.15.4. The results have shown that the new proposal outperforms the compared standard. That is, related to IEEE 802.15.4, DyTEE obtained a reduction of approximately 7 times in power consumption. Also, an energy efficient actuating board was used to compare the impact of a MAC (Medium Access Control) protocol on a node battery charge. Thus, the MAC layer was responsible for up to 99% of the energy used in a node operating a frequent irrigation schedule (once a day), concluding that the new protocol has a good energy saving while keeping simple implementation. However, the energy consumption of a MAC layer had a high impact and should be taken into account in an automation environment. Hence, the use of a more suitable protocol for the desired application can extend the lifetime of its nodes.

Keywords— Energy Efficiency, MAC Protocol, Rural Automation, Wireless Sensor Network.

1 Introduction

The possibilities of automation in some systems are almost unlimited. Thus, the focused systems in this work are building and rural automation with slow rate acquisition sensor, like temperature, humidity, soil moisture, and similar. Actuators are also important elements, like starting an engine, an air conditioner, or even opening and closing valves for irrigation.

However, the modules used by these automation systems are communication dependent; that means, they generally need to communicate between each other to inform parameters, results, and actions. In rural automation this necessity appears too, sometimes combined with the lack of available points of constant energy source, differently from an industrial environment. As an example, inside an irrigation process, large fields with no near energy source are commonly seen. Hence, batteries are likely to be used, so that cables can be dismissed either for communication or for supply.

Searching for better and accessible solutions, wireless sensor network (WSN) applied to building and rural automation has been largely used where communication through cables is not as easily managed or installed as wireless systems are. Specifically in rural environments, underground cables are also subject to problems, like long distances and electrostatic storms. As stated by Nikolidakis et al. (2015), the need for human intervention can be minimized. For these reasons, it is expected that WSNs will become a low cost yet effective approach for the monitoring of rural fields in near future.

According to Nikolidakis et al. (2015), irrigation is one of the main water consumers throughout the world. Almost 60 percent of the world's water, taken from rivers, lakes, reservoirs, and wells, is used for irrigation. Besides, agriculture plays a vital role in economy, at the same time as it interacts with several industries. By Coelho et al. (2005), irrigated agriculture represented 18% of the total cultivated area in the world, consuming 70% of the used water, over the industries (21%) and domestic usage (9%). This shows how important agriculture precision is, in its smallest details.

An important policy in many cultures resides in the frequency and duration of the irrigation process, because delayed or flooding irrigation will probably damage or reduce production, or even weaken the culture due to more infections. Hence, growing cultures may sometimes be a complex and demanding work, which requires study and experiments. In this work it will not be treated that way, as it is not the main subject here. Thus, this paper deals with the importance of a specialized developed MAC protocol, called DyTEE (Dynamic Time Energy Efficient) (Guimaraes et al., 2015), for building and rural automation systems. The irrigation process will be considered as simple as measuring soil moisture, starting pumps for water, and opening/closing valves. Accordingly, actuating frequencies will be considered as a value of times a week.

As discussed before, in rural automation, battery comes out as the best solution, sometimes associated with solar recharging. Another important consideration about these automations is that they both may use, generally, low size messages for sensing and actuation, besides being not very sensitive to delays. Not all cases of automation have these features, but this specific one considered for this work, allowing the system to prioritize energy saving over latency or throughput, provides the desired goal, which is having the network alive for as long as possible. According to Handziski et al. (2004), the energy consumption during wireless transmission may be 12 times higher than its own processor, in the case of Telos motes. Thus, as stated by Doudou et al. (2016), energy saving highly depends on the MAC layer by duty-cycling the radio and switching between active/sleep modes, which orchestrates the device's whole working cycle. Hence, the design of energy aware MAC protocols is an important issue for WSN used for this kind of automation.

The main purpose of this work is to evaluate the energy expenditure of a new developed MAC protocol inside an automation system, as communication procedure is responsible for most of the energy budget of a WSN module for this case.

The remainder of this article is structured as follows. Section II presents related works. Section III expounds the methods used to measure performances and comparisons. Section IV presents the results in testbed motes through experiments followed by the conclusions.

2 Related work

Rural automation, targeting mainly the irrigation system, could be done in many different ways, from simple temporized on/off opened loop process to a fuzzy decided form, to determine when to irrigate, based on sensors in the environment.

In Vellidis et al. (2008), an RFID module coordinated with a microcontroller was used to sense soil moisture and soil temperature (through thermocouples), all supplied by a 9V battery. As these modules were designed to sleep and operate in low consumption most of the time, their achieved life time was enough to run test through all growing season period (June to September). Through a closed loop process, this work was able to demonstrate the gain of an automation process compared to a manually executed service done by an experienced worker. Results have shown that precision irrigation through soil sensors could stabilize the water conditions for the culture during the whole time, while the manual irrigation side stood dry for some time or too wet in other moments. This proves that automated irrigation achieves the desired goal for crops, avoiding waste of water and even damage to the culture.

Nowadays, RFID communication may not be the best option to use, since cheaper, faster, and more energy efficient options are available. However, in some cases, non usual systems are still seen in recent works. Distance, accessibility, and other reasons may justify the use of them, as seen in Jagannathan et al. (2015), who designs his system based on GSM communication modules, so that their sensors and actuators are controlled through it. GSM modules may consume a lot more than other simple communicators and have even higher costs since they use one GSM microchip/account per module applied.

Although automated irrigation may bring improvements to the agriculture, the methods and decision process may vary from culture to culture. Some plants may require different sensors with specific sampling rates; others, even multi-sensor knowledge-based controllers. In this way, Al-Ali et al. (2015) uses fuzzy logic to decide when to irrigate, based on temperature and soil moisture sensors under the ground. They also used Zigbee network to communicate master nodes with slave nodes, which resulted in a good energy saving system. However, their main focus was on the irrigation process and when to operate, not the battery duration of the nodes.

Aware of energy saving, Nikolidakis et al. (2015) treats not only the water efficiency problem, but also the routing among nodes. They propose the use of ECHERP, a routing protocol that pursues energy conservation by selecting the best cluster nodes along network. This work still used the Zigbee protocol to communicate their nodes, but already demonstrate the attention with the energy conservation, searching for better ways to save energy for a specific application.

Other WSN protocols were developed focusing energy efficiency. A commonly used protocol of comparison, known as S-MAC (Ye et al., 2004), is a consolidated approach for energy-saving, which was implemented in a real platform. It has features that contribute for the rationing, like activation and sleep cycles (duty cycles), small packets for traffic control similar do the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol that enables low energy loss in case of a collision. According to Ye et al. (2004), this protocol was developed to meet the need of energy saving at the cost of increased latency.

Since then, recent works have developed even better energy efficient protocols, some operating with CSMA/CA logic, others with TDMA (Time Division Multiple Access), or both. The main difference is that a CSMA/CA protocol, generally, allows solving the latency problem while still trying to reduce energy consumption, offering a good end-to-end delivery time. Moreover, TDMA protocols offer an opportunity for better energy saving, though spending energy with beacons or schedule programming. In fact, idle listening, collisions, and overheads may bring down the efficiency, so most of the proposals are based on working with them to optimize its application needs.

In CS-ATMA (Carrier Sense Advertisement based Time division MAC) (Mishra et al., 2015), nodes are basically operating in a TDMA mode synchronized with a S-MAC mode. Nodes are divided into groups, which do not operate at the same time. After that, a node searches for a free slot inside its group with a clear channel access (CCA) method. Despite using a TDMA method, CS-ATMA still has some collisions inside the contentions realized by nodes to acquire a slot of the group, and thus wasting energy.

In a hybrid approach, Doudou et al. (2016) developed a MAC protocol capable of switching between TDMA and CSMA mode. During its normal operation, nodes communicate in cascade, from end-device to the sink node, like DMAC (Lu et al., 2004). Hence, latency for data acquisition is very low when the traffic load is also low. However, when traffic becomes high or nodes have real-time delivery necessity, this protocol also offers a CSMA window between sleep periods of the TDMA communication. This allows fast communication for real-time applications, but also spends energy with idle listening and packet collision.

Observing this lack of attention on the MAC layer in building and rural automation systems, a focused energy efficient protocol called DyTEE (Dynamic Time Energy Efficient) was developed. Also, DyTEE was implemented in real motes from Atmel, called Zigbit. This protocol considers the application for environments with:

- Low throughput, because the data generations is not very frequent, nor large (usually less than 100 bites);
- Possibility of high latency (in some cases, delays of minutes are tolerable);
- Low density of nodes;
- Low connection dynamics, that is, nodes tend to connect to the network and remain there until exhausting their energy; and
- High efficiency in energy saving to attain increased longevity.

As stated in Guimaraes et al. (2015), DyTEE operates with single channel clusters and clear channel assessment (CCA) only, through duty cycles and timed slots (TDMA), as the form of possible prevention of collision. Nevertheless, collisions do not occur unless a node is trying to register during the REG period (using CSMA). Therefore, packet collision and idle listening are not considered tolerable, achieved at the cost of latency and throughput. For a multi hop transmission, nodes of one cluster may operate as leaf for a moment and as coordinator of another adjacent cluster during the sleep period of the its father cluster. In this way, adjacent clusters can operate in the same channel and still have no collisions.

Another important feature in DyTEE is that a coordinator node (presumably capable of measuring its own battery level) will end its own cluster after a certain predefined percent amount of consumption, letting its cluster leafs start another competition for coordination of this cluster. The higher the battery level, the faster a node will start the process to become a coordinator. This process allows the network to deplete batteries evenly.

Each node has a simple sequence of tasks based on what happens around it, which can be expressed as a flowchart. Hence, Fig. 1 presents each event and situation that a node may operate while executing the protocol, where each block represents a time slot in its moment of the protocol (TDMA like).

It is important to remember that each node may try to become leader at its initialization, but only if it does not hear any beacon signal (BS) from other nodes, as pointed in Fig. 1. Thus, being leader makes this node operate differently.

Moreover, there is a standard IEEE 802.15.4 (*IEEE Standard for Local and metropolitan area networks–Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs), 2011*), which can be considered a state of the art, since it is the foundation of Zigbee protocol used in many works. It provides blocks of communication (superframes) containing small slots of time after a beacon signal. These slots are: ones “delivered” by contention, others guaranteed, followed by sleep periods like S-MAC. One of the advantages of this standard is that it has a variety of configurations, allowing its design to fit in most of the applications.

3 Methods

DyTEE and IEEE 802.15.4 (base of Zigbee and standard in WSN systems) will be considered applied in a hypothetical automation environment for the purpose of investigating the behaviour of this previous developed MAC protocol. As the desired application operates, a tree-like topology of networks is the closest model to represent the direction of data through it, and so the creation of cluster is done from the sink node to the leafs.

Important to notice that, since DyTEE and IEEE 802.15.4 have similar parameters, it was possible to set both close enough to be compared. Thereby, measures with real motes, built with Atmel Zigbit modules supplied directly with 2xAA battery cells, could have been made. Communication was made in a star-like topology, where all leaf nodes reach the leader directly.

Since multi-hop measures are more complex, in this experiment, only a single hop cluster was created for both protocol experiments. Hence, DyTEE was implemented and compared with the standard implementation of the IEEE 802.15.4 protocol, also available for these motes. And so, experiments of communication energy consumption were separated by transmission rate (varying from 1 second interval to 10 seconds). Each rate of transmission was repeated 10 times.

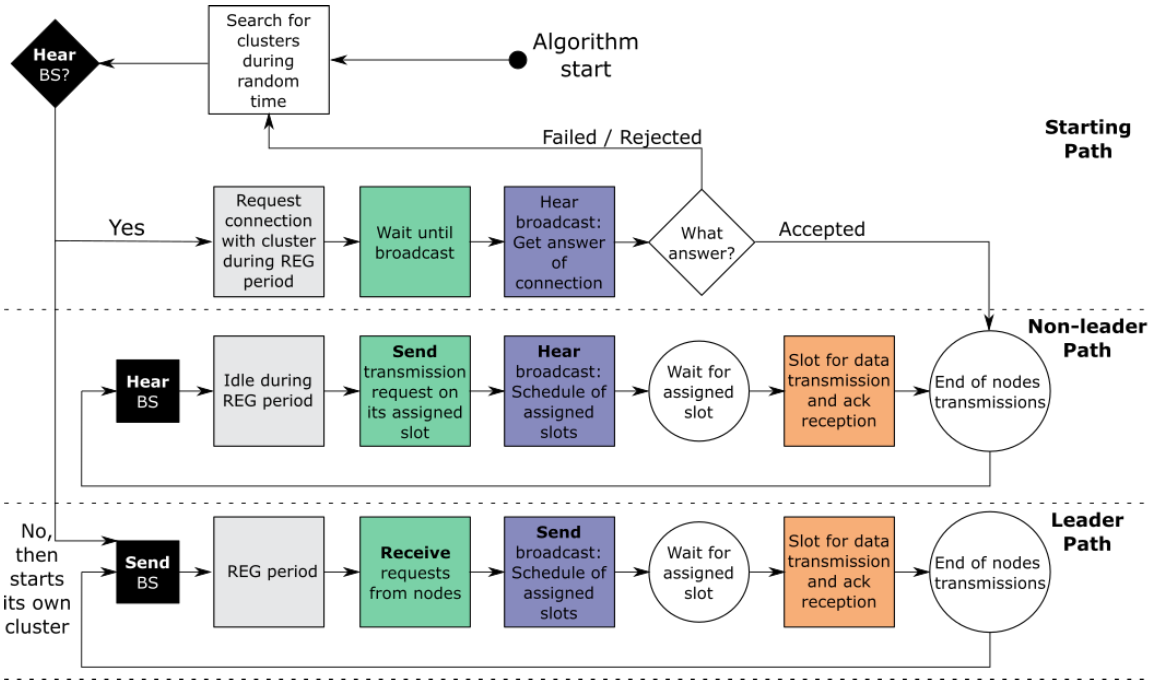

Figure 1: Operation flowchart for a node executing the DyTEE protocol.

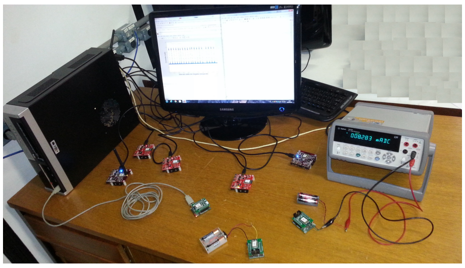

Figure 2: Process of current measuring of a leaf node (battery connected).

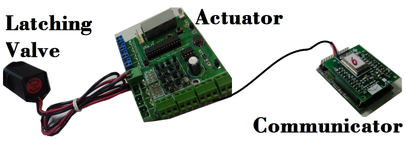

Figure 3: Actuator/sensor board for irrigation.

For a rural automation, a network composed of one sink (leader) and leaf nodes for sensing/actuating can be considered a basic automation environment. In this case, the use of a developed board (Fig. 3) for sensing and actuating is applied, comparing both protocols. This board is capable of opening/closing a latching solenoid for a water valve without wasting high amounts of energy like an AC valve would. Also, it can measure soil moisture and calculate water flow. Therefore, communication is done through the Zigbit module, capable of waking the board when necessary.

To compared the expenditure of a MAC layer inside an automation system with a simple actuating and sensing task, measures of current consumption from both radio modules and irrigation board were evaluated separately. As stated by S-MAC authors (Ye et al., 2004), measuring each state instrumentally is a hard procedure, especially for long experiment durations. So, a workaround for this was setting the motes to count how many bytes it had sent or received, and the total time in wake up mode. Then, knowing the consumption in each mode (sleep, wake up, transmitting, and receiving), the time needed to switch states, and de time needed to transmit an amount of bytes, it was possible to estimate the total consumption of this node as well as the parameter, like throughput and overhead.

Nevertheless, the current measure process was also confirmed using a 34410A Agilent (multimeter). Through recorded samples, a current expenditure was obtained and, with its integration, the energy consumption was calculated, filtering only the radio consumption to be analysed. However, only the results obtained from the counting method will be presented, as it provides enough confidence, with a mean of 10 experiments.

4 Results

In this work, DyTEE was compared with the standard IEEE 802.15.4. Accordingly, the zigbit motes used in this work are an integration of a communication layer (power amplifier, dedicated controller and its processes), a core microprocessor (responsible for application layer and orchestration of the whole module) and peripherals (ADC, actuator, sensors and other). Thus, comparisons will only consider the energy expen-

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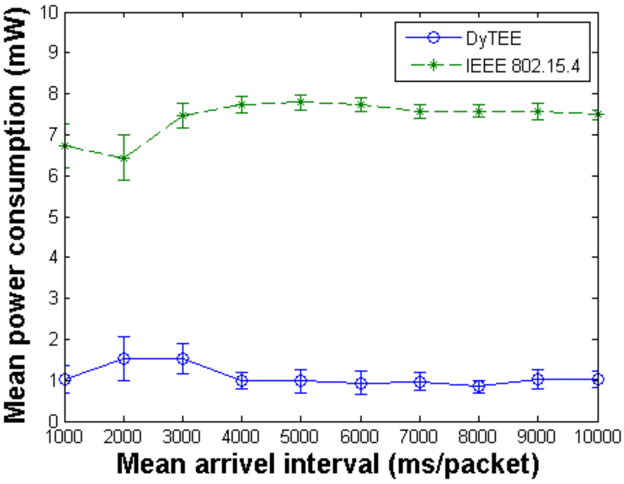

Figure 4: Mean power consumption of a node for DyTEE and IEEE 802.15.4 in implemented testbed motes.

diture of the communication layer, since this is the main actuation of the MAC protocol here analysed. And so, measures of the communication layer shown that power consumption modes are: reception 51.1 mW, transmission 54.45mW, and sleep 66nW. Also, the core microprocessor itself, when active, consumes about 8mA, which means about 26.4mW. The transmission rate is fixed at 250 Kbps and payload in both experiments used 20 bytes (not considering header, which varies in each protocol). Real energy consumption measured by both protocols are shown in Fig. 4.

The setup of IEEE 802.15.4 was:

- Superframe order 5 (No smaller value, implementation restrictions), equivalent to 500 ms of maximum active time;
- Beacon interval 6 (1 second interval);
- Also used 8 operating nodes, being one of them the coordinator; and
- Beacon enabled network and addresses of 2 bytes.

DyTEE was configured to have the same parameters, except for the superframe time, which is specific of the IEEE 802.15.4. DyTEE has, by design, a smaller "superframe" of about 60 ms.

Results show that, for the communication layer, IEEE 802.15.4 mean power consumption is 7 times higher than that of DyTEE (Fig. 4).

Also, although latency and throughput values are not shown here, a combined metric between throughput and energy consumption is presented (Fig. 5). This combined metric is calculated through the mean value of throughput divided by the mean value of the energy spent at each point. So, the higher the value, the better it is the result, relatively.

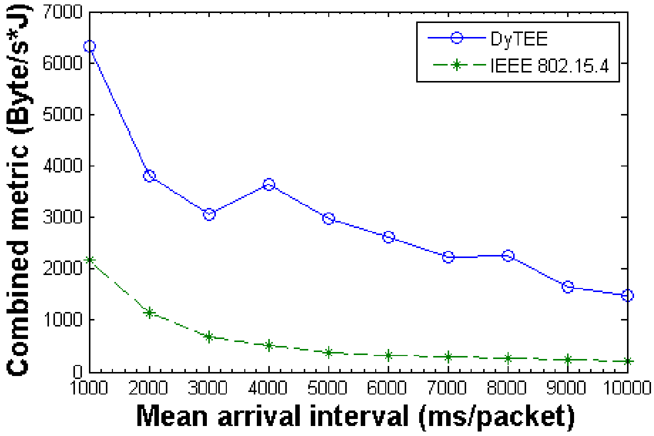

Figure 5: Combined metric of DyTEE and IEEE 802.15.4 in implemented testbed motes.

In other experiments, considering the core microprocessor together, DyTEE also obtained better results than IEEE 802.15.4, where DyTEE consumed 31.2% less current in the same modules. This represents battery duration up to 3.4 times longer in hours of operation. These results were obtained with an oscilloscope and a shunt resistor in series with the supply.

4.1 MAC consumption inside the automation

In real tests with the irrigation board (Fig. 3), it consumes as much energy as the communication module for the sleep mode and about 450mA for opening or closing a valve. The time required to charge the capacitors and open or close the valve is only 300 ms, supplied by a 3.3V battery. Considering a rural automation environment of irrigation during a dry period, with a periodic actuation of once a day, this would represent turning this irrigation board active only 14 times a week (2 times a day to open and close during 7 days). Then, the energy spent to open/close the valves would be

$$\begin{aligned} Energy_{Valves} &= 3.3V * 450mA * 0.3s * 14events \\ &= 6237mJ. \end{aligned}$$

Furthermore, the total energy spent by the MAC layer operating DyTEE during the week, with its mean power consumption, would be

$$\begin{aligned} Energy_{MAC} &= 1.028mW * 24h * 3600s * 7days \\ &= 621734.4mJ. \end{aligned}$$

For this comparison, sleep consumption of both modules were not considered, even because they are very similar. Further, these values show that activating once a day during a week, an irrigation board would consume 1% of the node total battery energy, leaving the other 99% to the MAC layer. Also, an irrigation board could spend more with other sensing procedures, but still this would not represent significant increase.

In a generally more spaced irrigation interval scenario, perhaps twice a week, the energy spent in valves would only represent 0.3% of the total battery expenditure.

5 Conclusion

This paper proposes the application of a developed MAC protocol called Dynamic Timed Energy Efficient (DyTEE), combining ideas from TDMA and CSMA to attain collision free data transmission, presenting low energy consumption compared to the standard IEEE 802.15.4 and S-MAC protocols. It also emphasizes the importance of the MAC layer in a real rural automation environment and how it impacts on the energy consumption of a WSN node capable of sensing soil moisture and opening/closing water valves. This protocol was specifically designed to operate in rural and building automation environments, saving energy at the cost of throughput and latency.

Results in testbed motes show that DyTEE could improve the energy saving of a node up to 7 times more than IEEE 802.15.4. Also, considering the use of a sensor/actuator board, this MAC layer would represent 99% of the total battery energy consumption. It demonstrates how influent a MAC layer can be in the node lifetime.

Future work will have this protocol tested in other platforms, expecting better results from implementation. In addition, the DyTEE will be compared in different applications, with different requirements. Also, it is important to improve the idea of a multi-channel and cross-layer protocol, which could result in better energy efficiency for the whole module.

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