An Adaptive Acknowledgement On-demand Protocol for Wireless Sensor Networks

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Abstract: The concept of packet acknowledgement in wireless communication networks is crucial for reliable data transmission. However, reliability comes with the cost of an increased duty cycle of the network. This is due to the additional acknowledgement time for every single data packet sent. Therefore, energy consumption and latency of all sensor nodes is increased whilst the overall throughput in the network decreases. This paper contributes an adaptive acknowledgement on-demand protocol for wireless sensor networks with star network topology. The goal is to tackle the trade-off between energy efficiency and reliable data transmission. The proposed protocol is able to detect network congestion in real time by constantly monitoring the overall packet delivery ratio for each sensor node. In case the packet delivery ratio of any sensor nodes in the network is dropped significantly (e.g. due to environmental changes), the protocol switches automatically to a more reliable data transmission mode utilizing acknowledgements concerning the affected sensor nodes. Our proposed method is tested and evaluated based on a specific hardware implementation and the corresponding results are discussed in this paper.

1 INTRODUCTION

In wireless sensor network (WSN) applications, the concept of packet acknowledgement (ACK) is often crucial because it is the best way for the transmitter to know whether the transmitted packets were received successfully. If the transmitter does not receive the ACK signal, it is concluded that the packet was not received, thus the same data needs to be retransmitted. Depending on the type of protocol used, the retransmission could be done in the next active time slot (scheduled based topologies) or it could be done until a certain time-out is reached (IEEE, 2011). However, it is obvious that those approaches increase the overhead of the data frame format and require a certain delay in order to receive the ACK signal. In turn, this delay can have a negative effect on long-term energy efficiency of low power WSNs. This is because energy efficiency is strongly correlated with the sensor node's duty cycle in WSNs. Thereby, the duty cycle refers to the cyclic ratio of active time (transmitting and receiving) vs. sleep time in schedule-based topologies.

Reducing ACK time is also directly related to the throughput in WSNs. Since the throughput is limited, not only by the transmission time of the packets, but also by the transmission time of ACK signals (Takamori and Yamao, 2015). At the same time, it is also directly related to the energy efficiency of WSNs. The reason behind is that the shorter the data transmission time, the longer the sensor nodes can stay in sleep mode. This allows extended operating times in battery-operated scenarios. This issue is even more relevant if the packet size of the transmitted data is comparable to the packet size of the ACK signal, which is very often the case in WSNs (Takamori and Yamao, 2015).

The key contribution of this paper is the development of an adaptive acknowledgement on-demand protocol for WSNs, which is able to switch from non-acknowledgement (No-ACK) to acknowledgement (ACK) mode and vice versa. It is using time division multiple access (TDMA) channel access method. The switch over between ACK and No-ACK- depends on the condition of the network congestion. With the proposed Acknowledgement On-Demand Protocol, we aim towards improving the overall energy efficiency, latency, and throughput in WSNs. Furthermore, we describe how the reliability of data transmission in star network topologies with TDMA scheme can be achieved effectively without using ACK. The proposed protocol was tested indoors with a specific hardware implementation simulating a typical smart home environment.

This paper is organized as follows: In section 2, the related work of the proposed concept is presented, followed by the system model of the proposed adaptive protocol in Section 3. The results of experimental evaluation and summary are presented in Section 4. The current limitations of the proposed protocol is described in section 5 and finally, the paper is concluded in section 6.

2 RELATED WORK

We found that very few papers in the literature explore how to efficiently reduce the packet ACK time in sensors networks for reliable data transmission. Concerning this, we briefly discuss previous related work that supports and highlights our proposed approach in this section.

In this regard, the group ACK method in a star topology of sensors network (Takamori and Yamao, 2015) was proposed to reduce the duration of the ACK time. With this approach, the network performance was improved and the bottleneck problem of the sink node (or central node), where the communication traffics are concentrated, was reduced. Also, the turnaround time of the antenna and the duration of total ACK time was reduced. This is because instead of sending individual ACK signals for every single transmitted data packet, a multiplexed group ACK signal is sent once in the preceding communication frame. The variable-period group ACK method is the best choice in all of the three methods for reducing the average time delay. Also, both fixed- and variable-period ACK methods outperform the normal individual ACK method. With their contribution, they highlight how the extended time frame due to ACK signal affects the performance of the whole WSNs. However, their approach is not based on network congestion and could lead to unnecessarily sent ACK messages.

Moreover, the comparison of ACK and No-ACK modes in sensors networks on end-to-end delay and throughput was analysed by (Al-Sharbaty, 2014). In their work, fixed and mobile sensor nodes are compared for tree and mesh topologies using the Zigbee protocol [1]. According to the simulation results, the choice of ACK or No-ACK influences the performance of the network, which also depends on the topology type that is used in the above mentioned two states of sensor nodes. According to the authors' findings, the end-to-end delay of the No-ACK is generally shorter than ACK in both fixed and mobile sensor nodes states. In the same way, the overall throughput of No-ACK is generally higher compared to ACK in both mentioned states.

Packet loss analysis for the No-ACK mode of IEEE 802.15.4 MAC (Shu et al., 2007) was presented with a non-stationary Markov Chain on the beacon enabled star topology. Moreover, the accuracy of the model was verified with the simulation results. It was concluded that the packet loss rate in No-ACK, in general, will increase in a network with more nodes and bigger packet size. This could be overcome with our approach by taking advantage of prior knowledge of reliable data transmission in a specific network scenario.

A dynamic adaptive acknowledgement strategy was presented by (De Oliveira and Braun, 2005). They improves the performance of Transmission Control Protocol (TCP) in multi-hop wireless networks by dynamically adjusting channel conditions. Another approach that effectively performs congestion control in WSNs was presented by (Scheuermann et al., 2008). Their evaluations are specifically focused on the issue of TCP congestion control in the transport layer of wireless ad-hoc multi-hop networks. However, the impact of ACK in single hop centralized network scenario was not fully investigated.

In this paper, the presented protocol is based on TDMA scheme because it is one of the promising approaches for latency and energy efficient prioritized applications in low power WSNs (Hadded et al., 2015). For instance, the TDMA-based e-health WSNs (Gama et al., 2010) and a resource allocation scheme in wireless body sensor networks (Liu et al., 2016) were implemented with TDMA to optimize both energy efficiency and quality of service (QoS). Another example of TDMA can be found for WSNs operating in noisy environments where it is used to avoid packet collision (Montiel and Cárdenas, 2014). Besides, the comparative analysis of a contention based and TDMA based MAC protocols for WSNs (Chand and Kakria, 2015) has shown that the TDMA based protocol outperforms contention based protocols in terms of averaged end-to-end delay, packet delivery ratio, and average energy consumption.

By far, all related work mentioned in this section focuses on the best and appropriate static method of

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[1] http://www.zigbee.org/

the protocol for WSNs before the network is actually deployed in a specific area. Thus, they are designed to perform well in a static situation. However, there are certain cases, in which the trade-off between energy and latency efficiency made is unnecessary and can be optimized if prior knowledge of the network congestion is effectively applied.

However, our proposed protocol differs in many ways from that of the above-mentioned approaches. Firstly, the decision whether No-ACK or ACK mode should be used for a specific sensor node is determined by the central node itself after the network is properly deployed in a certain area. Secondly, the proposed protocol has the ability to adapt to the current network congestion and is able to switch from No-ACK to ACK mode for particular sensor nodes if necessary in order to maintain the highest energy efficiency. Calculation of packet delivery ratio (PDR) between transceivers for reliable data transmission without using ACK in TDMA based WSNs is presented in this paper. To realize energy efficient data transmission, our proposed protocol uses TDMA without ACK (No-ACK) for the sensor nodes in the uncongested network scenario and TDMA with ACK is used for the congested network scenario. This dual approach is chosen in order to increase the reliability of the data transmission while maximizing the energy efficiency. The implementation details and test results of our proposed adaptive protocol are given in section 3 and 4.

3 SYSTEM MODEL

3.1 Hardware Design

In order to test our proposed networking concept in hardware, we implemented exemplary sensor nodes and a central node using the *BRIX*$_2$ prototyping platform [2]. *BRIX*$_2$ (Zehe et al., 2012) consists of a base module that can be combined with optional extension modules (Fig. 1). These extension modules allow to add functionalities to match a desired application. The *BRIX*$_2$ base module contains an Atmel ATmega32U4 and an ATmega328P microcontroller, a Texas Instruments CC1101 Radio Frequency (RF) transceiver operating in the 868 MHz ISM band, an Invensense MPU9150 IMU as well as a 450 mA Li-Poly battery. The compact form factor of *BRIX*$_2$ and the software framework based on Arduino[3] allowed us to rapidly develop, modify and deploy an exemplary WSNs.

Figure 1: Base module and extension modules of *BRIX*$_2$.

3.2 Data Frame Format of the Proposed Protocol

All conducted tests and results presented in this paper are solely obtained by using *BRIX*$_2$ devices. To reduce the overhead, only a single data format is used for both the receiver and transmitter in our proposed protocol (Fig. 2). The protocol is evaluated with star network topology. The message size of the physical layer for *BRIX*$_2$ is 29 bytes with a user control data payload of 20 bytes. The user control frame is composed of the senders address, the frame control section, the length of the message sent and the payload. The frame control section is responsible for controlling the message flow in the network. The reason why we use only a single sender address in our proposed implementation, is that the data transmission in a star network topology is simply between the central node and the sensor nodes. Thus, it can easily be identified with just the sender's address. The data frame format for the physical layer has already been defined in the library of *BRIX*$_2$.

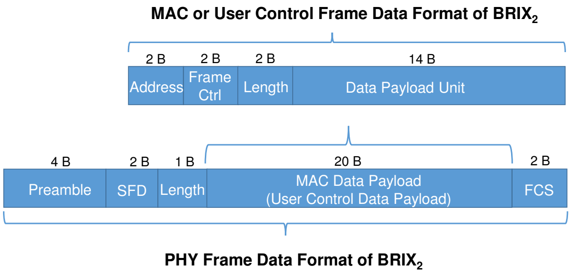

Figure 2: Data frame format of the proposed algorithm with minimum overhead.

3.3 Time Slot Allocation in TDMA

In TDMA, each sender is allocated to a certain time

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[2] https://www.techfak.uni-bielefeld.de/ags/ami/brix2/

[3] https://www.arduino.cc/

slot. With this mechanism, a single carrier frequency can be shared among different sensor nodes without risking packet collisions. Figure 3 describes the time slot allocation for TDMA scheme implemented in *BRIX*$_2$ device for testing the proposed protocol. The time slot for each sensor node in TDMA depends on the number of bytes that are to be transferred. This number changes with the packet size and the decision between ACK and No-Ack mode. It follows that duty cycle and throughput of a sensor node in TDMA are directly associated with the active time of that sensor node and the *FrameTimeSlot* of the network. In fact, the active time depends on the size of the data payload and the ACK or No-ACK mode (Fig. 3). In the same manner, the *FrameTimeSlot* depends on the active time of every sensor node in the network with their corresponding guard time slot and the number of the sensor nodes in the network.

3.4 Algorithm of the Proposed Adaptive Protocol for WSNs

The duty cycle is the key factor for energy efficiency in TDMA based WSNs as previously mentioned. Therefore, our proposed protocol is evaluated in this manner. This is because the energy consumption of a sensor node in WSNs is determined by the sensor nodes' current consumption in transmit, idle and sleep mode, which is 16.8 mA, 1.7 mA and 100 μA in *BRIX*$_2$. To maximize the energy efficiency and maintain the reliability of the network, we proposed an adaptive acknowledgement on-demand protocol for WSNs. The flow chart of our proposed protocol is depicted in Figure 4 and could be summarized as follows:

- An initial network congestion test is done by sending predefined packets without ACK. This is done after the sensor nodes are actually deployed in a specific network area.
- If the packet delivery ratio (PDR) of a sensor node in the network is higher than the predefined threshold value, the central node uses the No-ACK mode for this particular sensor node. Otherwise, ACKs are used.
- During data transmission using the No-ACK mode, a continuous network congestion test is carried out. It is done by constantly monitoring the PDR of each sensor node. This allow to react to temporary changes in the network. Based on the PDR soft margin threshold, automatically switching to the ACK mode is done in case failure of one or more sensor nodes is detected.
- In order to identify whether switching to the ACK mode is caused by a temporary or permanent changes in the network environment, the protocol is able to switch back to the energy efficient No-ACK mode once an adjustable countdown timer runs out.

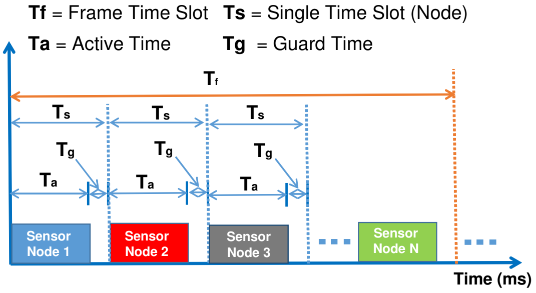

Figure 3: TDMA scheme of the proposed protocol.

The assurance of PDR is the central process in the proposed algorithm. The monitoring process of the algorithm is mainly based on counting how many times data from a certain sensor nodes is received by the central node. The PDR calculation for No-ACK mode is based on the received packets counter and the TDMA frame cycle time.

For a reliable and energy efficient data transmission, the proposed protocol allows a mixed mode which is ACK and No-ACK modes are applied together in the network. Since we are able to determine which sensor nodes fail to send data in the network, we can efficiently switch to a different mode for every sensor node on demand. The idea is that the non-failing sensor nodes will continue transmitting data using the No-ACK mode while the failing sensor nodes are switched to the ACK mode to guarantee reliability.

We expect that in the described way, unnecessary energy consumption and latency caused by the ACKs in WSNs can be reduced. The adaptability of the proposed protocol makes the network able to combine the benefits of the energy efficiency in No-ACK mode and the robustness in ACK mode on demand.

4 RESULTS AND DISCUSSIONS

The energy consumption in WSNs basically depends on the duty cycle and packet size of the sensor nodes, which is directly associated with their active time. In fact, the duration of the active time depends on both the data transfer speed of the network and the type of protocol used in the network (Hadded et al., 2015). In this section, we focus only on the latter and compare the results of using ACK, No-ACK and mixed modes in sensors networks. To discuss the results,

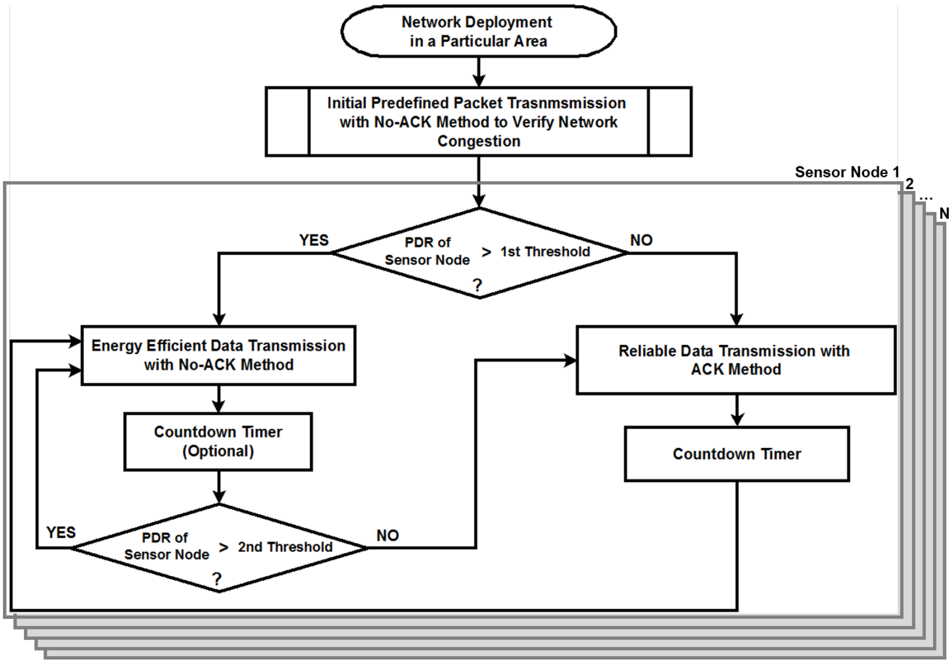

Figure 4: Proposed algorithm of the adaptive acknowledgement on-demand protocol for wireless sensor networks.

we provide network parameters such as packet delivery ratio (PDR), data throughput, active time and duty cycle of the sensor nodes. The tests are conducted using *BRIX*$_2$ modules with widely used existing protocols namely the un-slotted CSMA/CA method implemented in accordance with the IEEE 802.15.4 standard, TDMA with ACK and TDMA without ACK. The RF interface of *BRIX*$_2$ is set up to 868 MHz frequency band with 0 dBm transmit power using the Anaren Integrated Radio 66089 series antenna.

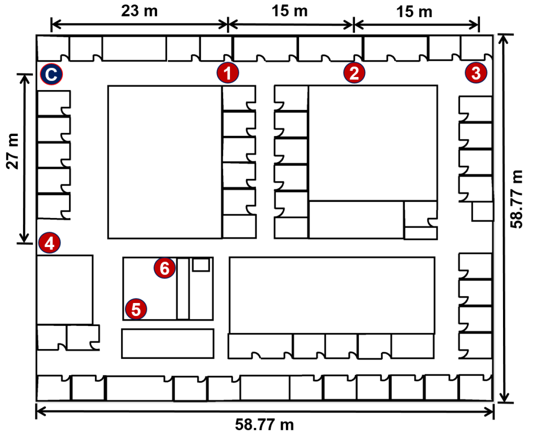

Figure 5: Indoor office environment test setup for packet delivery ratio.

4.1 Packet Delivery Ratio

The test setup created to measure the PDR is done in an offcie indoor, simulating a typical smart home environment. The building is mainly constructed using steel and glass. For the experiment, 6 sensor nodes were deployed across the building along with a central node to retrieve the data from the deployed sensor nodes (Fig. 5). In this scenario, 3 sensor nodes, (node 1, 2 and 3) are located in the direct line of sight (LOS) with the central node along the corridor. The other 3 sensor nodes (node 4, 5 and 6) are placed in non-line of sight (NLOS) locations.

For each test, 1000 packets were transferred with the maximum payload size of 20 bytes. All tests are repeated 50 times (Fig. 6). According to the test results, the average PDR of the nodes in LOS condition is 100 % in both the ACK and No-ACK mode (Fig. 6). Only node 3 shows a lower PDR (99.5 %) if tested in No-ACK mode. In the NLOS condition, the average PDR of node 4 is 100 % in both modes while it is 99.6 % for node 5 when tested without ACK. In gen-

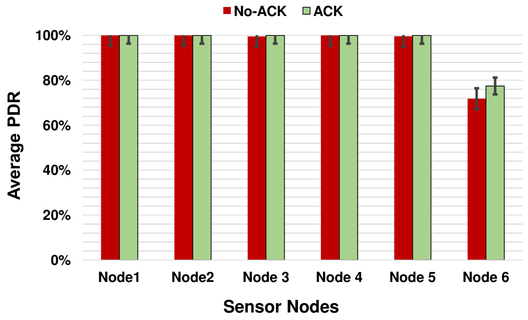

Figure 6: Comparison of the packet delivery ratio for TDMA with ACK and without ACK.

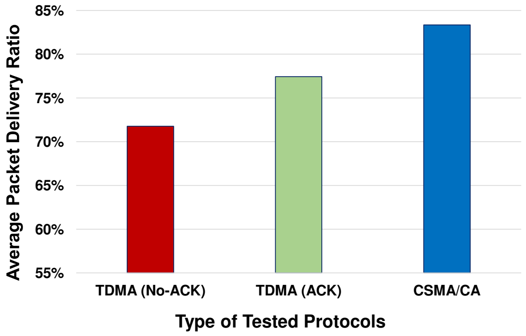

Figure 7: Comparison of packet delivery ratio for single sensor node in congested location 6.

eral, there are no significant deviations between the average PDRs (ACK vs. No-ACK) concerning node 1 to 5. However, differences in the average PDRs between ACK and No-ACK modes are found for sensor node 6. In the particular position of node 6, a higher average PDR is achieved when ACK mode is used (Fig. 6). In this context, one-time packet retransmission is allowed in TDMA using ACK mode.

Moreover, the test is conducted with different schemes to compare the average packet delivery ratio for a single sensor node (Fig. 7), which is placed in the position of node 6 (Fig. 5). Results show that a better PDR is reached in TDMA with ACK compared to TDMA without ACK. The highest PDR is achieved in CSMA/CA scheme, in which up to three packet retransmission are allowed. However, packet losses are occurred in all of the three tested schemes from this specific sensor node's location.

4.2 Data Throughput

Additionally, we compare the test results of data throughput for TDMA with ACK, without ACK and different conditions of mixed ACK and No-ACK mode (Fig. 8). For all tests, the maximum data size is 20 bytes. The graph represents the mean data throughput received at the central node for the whole network in 30 minutes. The ideal case (Fig. 8) refers to the data throughput measured directly between only two *BRIX*$_2$ modules with maximum payload and no channel access method.

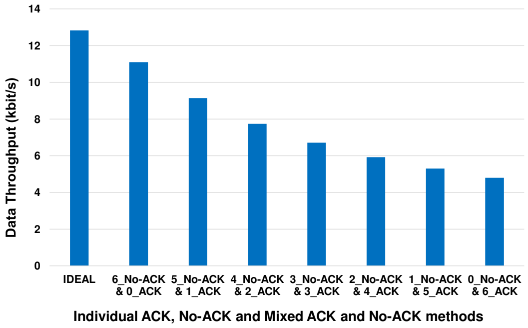

Figure 8: Comparison of data throughput in different schemes at run time period of 30 minutes.

The throughput declines as the number of sensor nodes that use ACK in the network increases. Thus, highest data throughput is achieved with TDMA in No-ACK mode. This value is also closed to the ideal value (12.83 kbit/s). Lowest throughput is received when all nodes are using ACK mode (4.8 kbit/s).

The reason that the data throughput of the ACK mode in TDMA is noticeably lower compared to the No-ACK mode is that the ACK requires additional waiting and processing time on both sides of the transceivers for the ACK signal. The problem of this ACK time becomes more crucial if the size of the ACK signal outweighs the data size ifself (or comparable to it). As previously stated, this is common especially in energy constraint low power and low data rate WSNs in which only small data packages are transferred.

4.3 Active Time of the Sensor Nodes

The active time of the sensor nodes is directly associated with the duty cycle. In turn the duty cycle is directly related to the energy consumption of the whole network. This is particularly true when the sensor nodes are transferring data through half duplex antennas. The active time of a sensor node, as explained in section 3.3, refers to the data transferring time plus the idle waiting time of ACK signal (in ACK mode) without going to their sleep mode. Therefore, we compare the minimum and maximum active time of the *BRIX*$_2$ module depending on the protocols that are used in the test (Fig. 9). In general, the active time for TDMA in the No-ACK mode is more than bisected compared to that of the ACK mode. Thus, the life time of the sensor nodes could be approximately doubled if the network is running with the No-ACK mode all the time. The minimum and maximum active times are

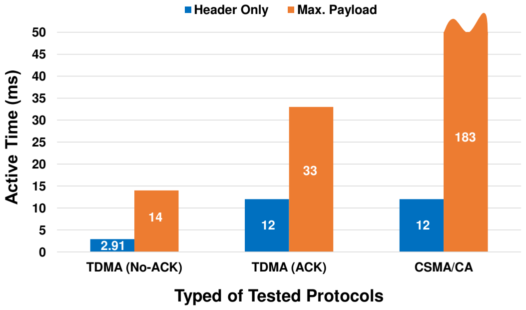

Figure 9: Comparison of minimum and maximum active time for three tested protocols in *BRIX*$_2$ module.

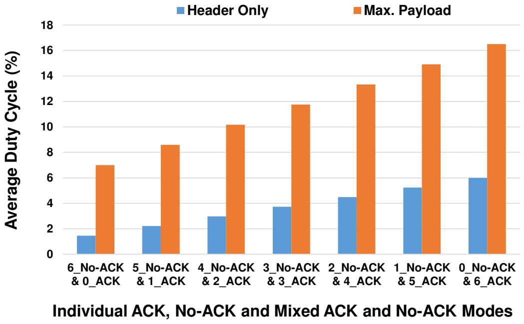

Figure 10: Comparison of the average duty cycle for ACK, No-ACK and mixed ACK and No-ACK modes.

measured for the two severe case scenarios:(i) header part only (no payload) and (ii) maximum data payload of 20 bytes. The maximum active time of CSMA/CA is based on the maximum random back-off time of the handshaking between the request-to-send (RTS) and clear-to-send (CTS) mechanism of the IEEE 802.15.4 standard.

4.4 Duty Cycle

The average duty cycle of each sensor node (Fig. 10) is based on the TDMA frame cycle of 200 ms when 6 sensor nodes are deployed in the network. This means the central node collects the data from each sensor node in the network every 200 ms. For both the header only and maximum payload data transmission, the lowest average duty cycle is found in the No-ACK mode with 1.4 % and 7 % respectively. Maximum average duty cycles (header and payload) with 6 % and 16.5 % are found when the ACK mode is used by all of the sensor nodes in the network. According to the test results, it can be concluded that the average duty cycle of the sensor nodes in the network would gradually be increased according to the number of the sensor nodes that are running in ACK mode.

4.5 Summary

According to the test results presented in this section, a mixture of TDMA with ACK and No-ACK should be used for energy efficient and reliable data transmission. For instance, node failure in sensor node 6 (Fig. 5) would cause all the sensor nodes in the network to switch to ACK mode in normal networking protocol. However, only node 6 needs to be switched to ACK using our proposed protocol. Thus, the data throughput will be 9.14 kbit/s instead of 4.8 kbit/s in which all the sensor nodes are using ACK mode. Simultaneously, the duty cycle of the maximum data payload will also be reduced from 16.5 % to 8.58 %.

5 CURRENT LIMITATIONS

With our current implementation of the proposed adaptive acknowledgement on-demand protocol for WSNs, the maximum number of sensor nodes that can operate in mixed ACK mode is limited by the total payload length of the protocol scheme. This is because the switching of the modes is controlled by the central node. This is done by individually adding the sensor node's identification number (IDs) to a broadcast packet. However, the scheme is subjected to be improved in a future implementation.

Moreover, the current switching time between the energy efficient data transmission with No-ACK mode to mixtures of ACK and No-ACK mode is from 100 ms up to approximately 1 second. This time depends on the number of sensor nodes in the network and the active and sleeping time of each individual sensor node. Again, we tend to improve this issue in a future implementation.

Furthermore, traffic differentiation between nodes will be accounted in the future implementation of the protocol to distinguish traffic classes such as high or low priority, real-time or best-effort.

6 CONCLUSION AND FUTURE WORK

In this paper, an adaptive ACK on-demand protocol for WSNs is presented. The protocol is tested on a hardware implementation using $BRIX_2$ devices. The impact of ACK signals in WSNs is highlighted by comparing network parameters such as data throughput, duty cycle, packet delivery ratio and active time of the sensor nodes. Two main concepts were deployed: Firstly, the protocol selection was done after all of the sensor nodes were deployed in a specific location in order to minimize the unnecessary usage of energy and latency caused by the ACK signal. Secondly, the data was transmitted in TDMA without ACK as much as possible in order to achieve maximum energy and latency efficiency. As a result, individual node failures can effectively be addressed using our proposed protocol.

However, the central node is expected to be connected to a continuous or large power source, since the proposed protocol is mainly focusing on the energy efficiency of the sensor nodes, which are solely supplied with a battery-based power source.

For future work, a simulation model for the proposed adaptive acknowledgement on-demand protocol for WSNs will be designed. The purpose is to further explore the impact of ACK in WSNs by varying the network parameters such as throughput, packet error rate, duty cycle and active time for both custom and general designs.

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