ICNS 2025

The Twenty-Frst International Conference on Networking and Services

ISBN: 978-1-68558-240-1

March 9th –13th, 2025

Lisbon, Portugal

ICNS 2025 Editors

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ICNS 2025

Foreword

The Twenty-First International Conference on Networking and Services (ICNS 2025), held between March 9 – 13, 2025, continued a series of events targeting general networking and services aspects in multi-technologies environments. The conference covered fundamentals on networking and services, and highlighted new challenging industrial and research topics. Network control and management, multi-technology service deployment and assurance, next generation networks and ubiquitous services, emergency services and disaster recovery and emerging network communications and technologies were considered.

IPv6, the Next Generation of the Internet Protocol, has seen over the past three years tremendous activity related to its development, implementation and deployment. Its importance is unequivocally recognized by research organizations, businesses and governments worldwide. To maintain global competitiveness, governments are mandating, encouraging or actively supporting the adoption of IPv6 to prepare their respective economies for the future communication infrastructures. In the United States, government's plans to migrate to IPv6 has stimulated significant interest in the technology and accelerated the adoption process. Business organizations are also increasingly mindful of the IPv4 address space depletion and see within IPv6 a way to solve pressing technical problems. At the same time IPv6 technology continues to evolve beyond IPv4 capabilities. Communications equipment manufacturers and applications developers are actively integrating IPv6 in their products based on market demands.

IPv6 creates opportunities for new and more scalable IP based services while representing a fertile and growing area of research and technology innovation. The efforts of successful research projects, progressive service providers deploying IPv6 services and enterprises led to a significant body of knowledge and expertise. It is the goal of this workshop to facilitate the dissemination and exchange of technology and deployment related information, to provide a forum where academia and industry can share ideas and experiences in this field that could accelerate the adoption of IPv6. The workshop brings together IPv6 research and deployment experts that will share their work. The audience will hear the latest technological updates and will be provided with examples of successful IPv6 deployments; it will be offered an opportunity to learn what to expect from IPv6 and how to prepare for it.

Packet Dynamics refers broadly to measurements, theory and/or models that describe the time evolution and the associated attributes of packets, flows or streams of packets in a network. Factors impacting packet dynamics include cross traffic, architectures of intermediate nodes (e.g., routers, gateways, and firewalls), complex interaction of hardware resources and protocols at various levels, as well as implementations that often involve competing and conflicting requirements.

Parameters such as packet reordering, delay, jitter and loss that characterize the delivery of packet streams are at times highly correlated. Load-balancing at an intermediate node may, for example, result in out-of-order arrivals and excessive jitter, and network congestion may manifest as packet losses or large jitter. Out-of-order arrivals, losses, and jitter in turn may lead to unnecessary retransmissions in TCP or loss of voice quality in VoIP.

With the growth of the Internet in size, speed and traffic volume, understanding the impact of underlying network resources and protocols on packet delivery and application performance has assumed a critical importance. Measurements and models explaining the variation and interdependence of delivery characteristics are crucial not only for efficient operation of networks and network diagnosis, but also for developing solutions for future networks.

Local and global scheduling and heavy resource sharing are main features carried by Grid networks. Grids offer a uniform interface to a distributed collection of heterogeneous computational, storage and network resources. Most current operational Grids are dedicated to a limited set of computationally and/or data intensive scientific problems.

Optical burst switching enables these features while offering the necessary network flexibility demanded by future Grid applications. Currently ongoing research and achievements refers to high performance and computability in Grid networks. However, the communication and computation mechanisms for Grid applications require further development, deployment and validation.

We take here the opportunity to warmly thank all the members of the ICNS 2025 Technical Program Committee, as well as the numerous reviewers. The creation of such a high quality conference program would not have been possible without their involvement. We also kindly thank all the authors who dedicated much of their time and efforts to contribute to ICNS 2025.

Also, this event could not have been a reality without the support of many individuals, organizations, and sponsors. We are grateful to the members of the ICNS 2025 organizing committee for their help in handling the logistics and for their work to make this professional meeting a success.

We hope that ICNS 2025 was a successful international forum for the exchange of ideas and results between academia and industry and for the promotion of progress in the fields of networking and services.

We are convinced that the participants found the event useful and communications very open. We also hope that Nice provided a pleasant environment during the conference and everyone saved some time for exploring this beautiful city.

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A Comparative Analysis of High-Level vs. Low-Level Simulations for Dynamic MAC Protocols in Wireless Sensor Networks

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***Abstract*—Simulation studies are conducted at different levels of details for assessing the performance of Media Access Control (MAC) protocols in Wireless Sensor Networks (WSN). In the present-day scenario where hundreds of MAC protocols have been proposed, it is important to assess the quality of performance evaluation being conducted for each of the proposed protocols. It therefore becomes crucial to compare the results of high-level theoretical simulations with the detailed implementation results before any network protocol could be deployed for a real-world scenario. In this work, we present a comparison of high-level theoretical and detailed implementation results for Adaptive and Dynamic Polling-MAC (ADP-MAC). MATLAB has been used for conducting initial theoretical simulations and TinyOS has been used to develop the detailed implementation of protocol for Mica2 platform. Performance evaluation of ADP-MAC using the two levels of simulation has been conducted based on energy and delay. In the high-level implementation, energy consumption was found to be decreasing whereas delay was found to be increasing for increasing channel polling intervals. On the other hand, when detailed implementation was developed, it was observed that both energy consumption and delay revealed an increasing trend with the increasing polling intervals. Therefore, it has been shown that the trends for high- and low-level simulations for ADP-MAC are significantly different, due to the lack of realistic assumptions in the higher-level study.**

Keywords—simulation; energy; delay; ADP-MAC; Mica2; channel polling

I. INTRODUCTION

Emerging applications of Internet of Things (IoT), such as smart city, wearable technology, home and industry automation and vehicular connectivity require state-of-the-art MAC layer protocols, which could facilitate optimal performance. Hundreds of MAC protocols for general as well as specific applications have been developed for the low power devices (Wireless Sensor Nodes & Networks) in IoT over the past two decades [1]. Due to the rapid emergence of industrial automation technologies and the role of IoTs, it has become crucial to identify the best suited MAC layer protocols [2]. Out of various performance parameters, energy and latency remain the hottest for managing the industrial communication networks.

The authors use various levels and tools for conducting performance assessment of their proposed MAC solutions. Often, authors present comparison of performance trends in MAC protocols using simulation, and testbed is rarely used due to the complications [3]. However, the match between the results of theoretical simulations and testbed experiments/low level simulations may not be possible to reach in every situation, particularly, when the details of WSN node or traffic characteristics are not possible to model completely [4]. Similarly, when the testbed experiments are conducted, the possibility of device malfunction and other real-world scenarios are better incorporated [5]. Despite high probability of missing out details in the high-level simulations, authors continue to present evaluation of their network protocols using the theoretical simulations [6], which creates hassles in transformation of the proposed protocols into real-world implementation. Therefore, there is a need to conduct comparison of the theoretical simulations results with those obtained after detailed testbed level implementation of the proposed protocols.

In the above context of studying the comparison of theoretical (high-level) simulations and testbed experiments (low-level), we present a comparison of results obtained for ADP-MAC. ADP-MAC has been developed with the motivation to timely serve the wireless sensor nodes through adjusting the polling interval distributions [7]. In comparison to the previous MAC protocols, which were designed based on altering the polling intervals [8], the novel contribution of ADP-MAC's design was to switch the 'polling interval distribution' instead of 'polling intervals'. Since no previous MAC was developed using polling interval distributions, the authors first tested the high-level idea of using interval distributions and simulations were performed at an abstract level using MATLAB [9]. Based on the satisfactory performance of initial results, the detailed implementation of ADP-MAC was developed for Mica2 platform, and the test-bed level simulation was conducted using Avrora. This paper describes the simulation results obtained through MATLAB & Avrora and offers a comparison of the two.

The primary motivation for this study is to address the limitations of relying solely on high-level simulations for evaluating MAC protocols, which often fail to reflect real-world conditions and challenges. High-level simulations provide initial insights but cannot account for practical issues like hardware constraints, packet collisions, and device malfunctions that affect real-world performance. By comparing the results of MATLAB simulations with testbed implementations on Mica2 motes, we aim to demonstrate the value of detailed, low-level evaluations in bridging this gap and ensuring the robustness of protocols like ADP-MAC for practical deployment.

Rest of this paper has been organized as follows: Section II presents a brief overview of the relevant work; Section III details the experimental set-up used for both simulation levels; Section IV presents the results and evaluation; finally, Section V concludes the paper.

II. RELATED WORK

Various adaptive MAC protocols have been developed for Wireless Sensor Networks in order to cater to the needs of recent applications of IoT [10]. One of the most efficient technique deployed in the adaptive MAC schemes is the dynamic duty-cycling where the nodes change their wake up and sleep duration based on the traffic arrival patterns [11]. Although these schemes have been quite successful, the protocols deploying dynamic channel polling (listening) have shown to even conserve more energy and adapt much better to the traffic requirements [12]. Hence, dynamic channel polling schemes are often required for the applications where energy conservation is of crucial importance, such as wireless body area networks [13].

An adaptive dynamic duty cycle mechanism for energy-efficient medium access control (ADE-MAC) has been proposed in [14] for Wireless Multimedia Sensor Networks (WMSNs). ADE-MAC employs an innovative asynchronous duty-cycle approach to manage the sleep patterns of sensor nodes, dynamically adjusting them based on the incoming traffic rate and queuing delays at each node; each node independently schedules its sleep patterns, requiring only the sender node to wake up the receiver nodes through the use of preamble packets. Although ADE-MAC significantly reduces synchronization overhead, it introduces increased delay due to the waiting time required for nodes to wake up. A variable duty cycle MAC (DC-MAC) [15] has taken synchronization approach by proposing a new method that only closely located nodes follow the same duty cycle, while the far-off nodes may follow a different. DC-MAC also has challenges due to synchronization overhead and high delay when need to send data to far-off nodes.

We proposed a dynamic channel polling scheme ADP-MAC in previous work [7]. The protocol was based on the idea that instead of altering the channel polling intervals as was the previous practice, polling interval distributions should be altered based on the analysis of the arrival distributions of traffic. For this purpose, we used statistical coefficient of variation (Cv) to identify the incoming arrival patterns. It was proposed that in case Cv is found to be higher than a certain threshold (0.8), exponential polling should be conducted, and deterministic polling should be used otherwise.

ADP-MAC is a duty-cycled asynchronous MAC in which the nodes begin their operation by sending preamble strobes, waiting for an early Ack, transmitting data packets and receiving final acknowledgement. In order to verify the impact of dynamic channel polling, we conducted performance evaluation for Constant Bit Rate (CBR) and Poisson arrivals and studied different types of polling: deterministic (channel polled at regular, pre-defined intervals), exponential (channel polled at exponentially distributed intervals) and dynamic (channel polling interval distributions switched between deterministic and exponential based on the traffic arrival patterns). Performance evaluation of ADP-MAC was conducted in two phases. Initially, MATLAB implementation was developed only to test the impact of varying polling interval distributions, and later a low-level TinyOS implementation was developed catering to the details such as collisions, preamble transmissions, retransmissions, etc.

A high-level study was conducted for the proposed dynamic channel polling mechanism in [9]. It was found that energy and delay performance both improve when exponential polling intervals are used for either CBR or Poisson arrivals. The rationale behind this finding was that when the channel is polled using exponential intervals, there is a higher probability of receiving aggregated packets. As a result, a single block acknowledgement could be used to send notification to the sender, which reduces the energy consumption. On the other hand, delay was found to be reduced for deterministic polling because packets could be received earlier due to having more regular polls.

In contrast, when the experiments were conducted for Mica2 using TinyOS implementation and Avrora simulator, it was found that energy consumption and delay both increase with increasing polling intervals. Also, the impact of arrival distribution was significantly visible over polling interval distribution: for CBR arrivals, it was found that deterministic polling serves best both in terms of delay and energy; for exponential arrivals, exponential polling served best and for bursty arrivals, dynamic polling was found to be the best choice. This finding was obtained because when the types of arrival and polling distributions match, there is a lesser delay between packet transmission and channel polling instant.

III. Experimental Set-up

The study was conducted in two phases: High-level implementation using MATLAB and low-level implementation using Mica2 platform and Avrora simulator. The experimental set-up details for each platform have been explained below:

TABLE 1: MATLAB SIMULATION PARAMETERS

Simulation Duration	5000 secs
Mean inter-arrival duration	5 secs
Mean polling interval	1-10 sec
Size of Data Packet	50Byte payload + 11Byte overhead
Size of Acknowledgement (ACK) Packet	10B
Size of Preamble	2B
Maximum no. of Concatenated in a Super packet	5
Energy consumed in Data transmission	0.5 mJ/Byte
Energy consumed in Single Data packet transmission	30.5 mJ
Energy consumed in ACK transmission	5 mJ
Energy consumed in channel polling	1 mJ

A. MATLAB Implementation Details

At this stage, to quantify the impact of deterministic and exponential polling interval distributions, a high-level algorithm was written in MATLAB, instead of developing a full MAC protocol. In the preliminary experiments, arrays were generated to represent the packet arrivals and channel polling intervals for a single hop network. Assumptions were made for the values of packet sizes, energy consumption and delay involved for each transmission/reception activity, as presented in Table 1. (taken from [9]; most of these assumptions were made based on the base protocol's (Synchronized Channel Polling-MAC (SCP-MAC)) implementation [16].

Experiments were conducted for different combinations of exponential & CBR Arrivals and polling interval distributions. The mechanisms of packet concatenation and block acknowledgement were also included in the

 ISBN: 978-1-68558-240-1

simulations; the packets which were received at a single poll were combined into a Super packet (packet concatenation) and a single acknowledgment packet was used to acknowledge the transmission of concatenated packets (block acknowledgements).

B. *Mica2 Implementation Details*

ADP-MAC has been implemented in TinyOS [17] over the Mica2 motes [18]. TinyOS is an open-source operating system designed for embedded sensor networks. The Mica2 motes used in this research features AVR ATmega 128L chip – a microcontroller produced by Atmel. Instead of running the code on testbed physically, Avrora emulator [19] has been used, which has the convenience and flexibility of quickly setting up the network of different topologies and varying the number of nodes. Avrora is a cycle accurate instruction level sensor network simulator; the scalability of this simulator is up to 10,000 nodes, and it is 20 times faster than its contemporaries that offer a similar level of accuracy [20]. The experimental configuration parameters have been shown in Table 2. Each experiment was run 4 times and the results have been presented with a confidence interval of 95%.

TABLE 2: PARAMETERS USED FOR ADP-MAC'S DETAILED IMPLEMENTATION OVER MICA2

Simulation Parameters	Value for ADP-MAC
Common Parameters	
Bit rate	18.78 kbps
Arrival Patterns	CBR/Poisson
Polling Interval Distributions	Deterministic/Exponenti-al/Dynamic
Total Nodes	10
Message Generation Interval	50 Sec
Number of packets transferred	20 packets generated by each node
Distance between the Nodes	1 m between each source and sink
Duration of Each Cycle T_{cycle}	10 sec
Threshold value of Cv	0.8
Size of Super Packet	Up to 5 data packets

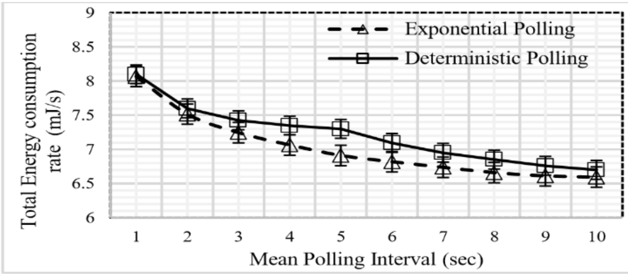
IV. RESULTS AND EVALUATION

The results for energy consumption comparing the MATLAB implementation and Mica2 simulations have been presented in Figure 1, whereas Figure 2 shows the delay performance.

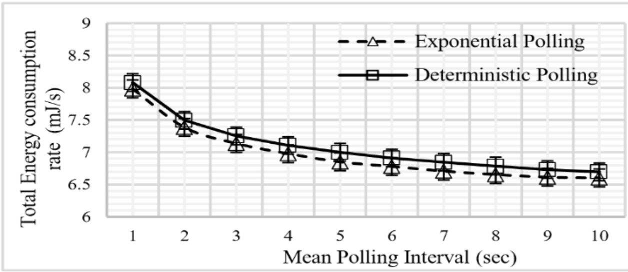
In the results obtained by high level implementation of ADP-MAC in MATLAB, it was observed that energy consumption decreases with the increase in polling intervals as shown in Figure. 1, where 1-a shows the performance of CBR arrivals, and 1-b presents the results for Poisson arrivals. On the other hand, the delay was seen to increase with increasing polling intervals as illustrated by Figure. 2; here Figure 2-a shows the delay trends for CBR, and 2(b) presents for Poisson arrivals; hence, a trade-off was found between the trends of energy consumption and delay, both for CBR and Poisson arrivals.

When the experiments for studying energy and delay performance of ADP-MAC were repeated based on the detailed low-level implementation of ADP-MAC, the trends obtained for energy consumptions have been shown in Figure. 1-c & 2-c. Here, it is to be noted that only trends can be compared but not the actual values; this is because in addition to lack of modeling real situation in the MATLAB implementation, there were also clear differences in the assumptions made for conducting MATLAB experiments and simulation parameters of detailed implementation of ADP-MAC

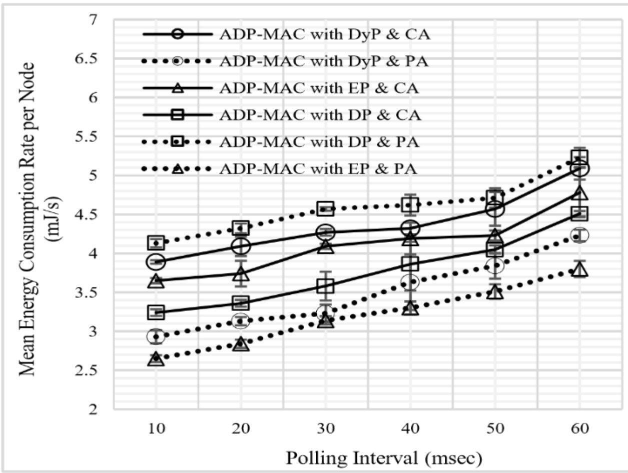
In contrast to the trade-off identified in the initial high-level simulations, there is no such trend seen in the detailed implementation results for ADP-MAC. Figure 1-c & 2-c illustrate that both the energy consumption and delay increase with the increasing polling intervals. Thus, the comparison for trends of energy consumption reveals an apparent contradiction between the initial high-level theoretical and detailed implementation results. However, for delay, both the initial as well as detailed implementation results reveal the same (increasing) trend with the increase in polling intervals.



(a)



(b)



(c)

Figure 1: Total Energy Consumptoon (a) High Level Results for CBR Arrivals (b) High Level Results for Poisson Arrivals (c) Results for Detailed Implementation

The second apparent difference between the MATLAB & TinyOS implementation results is that it was predicted by MATLAB results that Exponential Polling should result in better energy performance for both the arrival processes, i.e. CBR and Poisson. Similarly, the delay performance was expected to be better for the Deterministic Polling regardless of the arrival process. In contrast, the findings of detailed implementation have revealed that for each arrival distribution type, if the polling interval distribution type is similar, it results in better performance for both energy consumption as well as for delay; i.e. for CBR Arrivals, the Deterministic Polling results in better energy and delay performance, whereas for Poisson Arrivals, Exponential Polling has come out to be a better candidate.

The rationale behind the first difference between the expected and detailed implementation results is the fact that the high-level prediction results are based on several assumptions, which are not entirely valid in the detailed implementation. For example, in the MATLAB implementation, the energy consumption was calculated based on the assumptions about the level of energy consumed in polling activities and data & ACK transmissions. For both the deterministic and exponential polls, the mean number of polls were always shown to be the same with only a change in their distribution. The energy savings was depicted through the transmission of reduced bytes due to packets received as concatenated and block acknowledgements. However, there was no implementation of the preamble transmissions, collisions, Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) process and retransmissions; all these details have been taken into account in the actual implementation of the ADP-MAC, which have resulted differently due to the assumptions about realistic channel and network conditions.

Moreover, since the preamble transmission mechanism was not modeled in the theoretical results, the energy consumption showed decreasing trend as at the higher polling intervals, the number of polls reduced, and the block acknowledgements increased leading to the better energy performance. However, in the implementation, as the polling interval increases, the preamble transmissions increase; this increases the energy consumption as although the polling energy will reduce for this case but at the same time, the preamble transmission energy and collisions would increase. This happens because the channel remains occupied for longer intervals, as compared to the cases where the polling interval was set to a low value and the packet could be quickly transmitted.

The second difference about the trade-off shown between the energy and delay in the MATLAB results can also be justified. In the implementation, no such trade-off exists, and the energy and delay reveal similar increasing or decreasing trends for both the arrival patterns. This happens because for the cases where the energy consumption would be higher due to the preamble transmissions, excessive polling, collisions and retransmissions, the delay will also be higher and vice versa. This insight was hard to predict in the high-level results due to the lack of consideration of the details of preamble transmissions and the possible collisions and retransmissions.

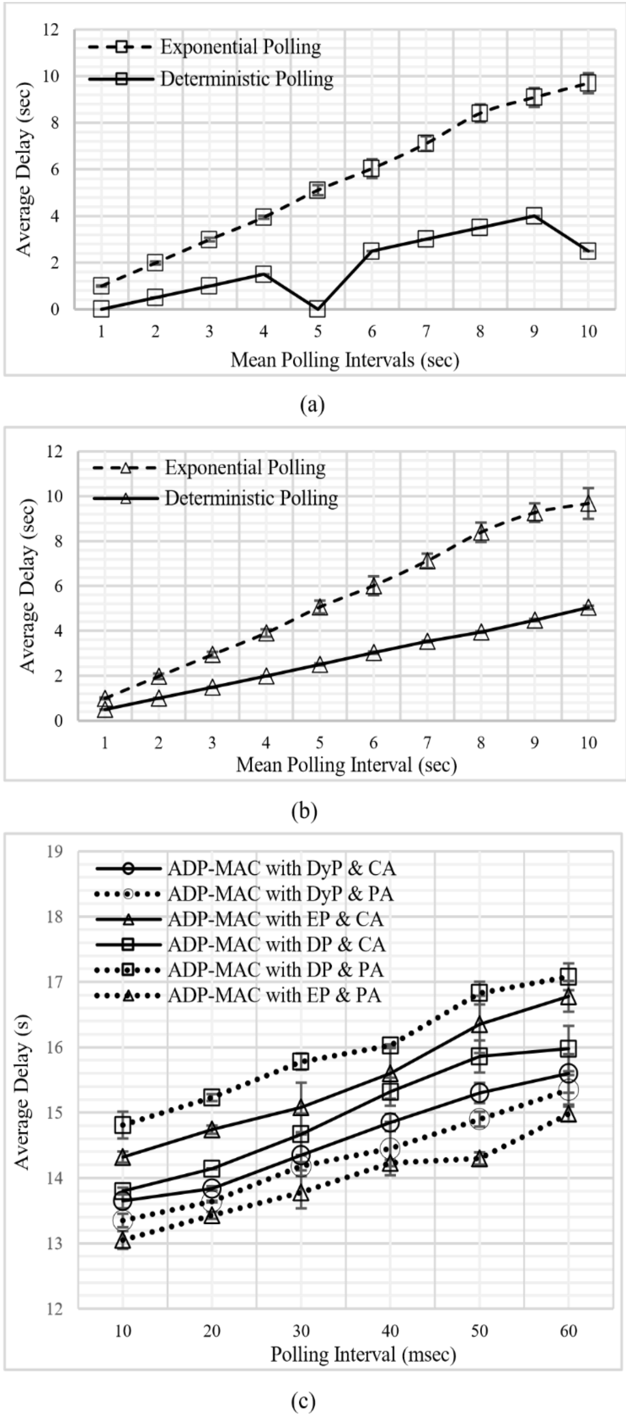


Figure 2: Average per Hop Delay (a) High Level Results for CBR Arrivals (b) High Level Results for Poisson Arrivals (c) Results for Detailed Implementation

On the other hand, the results for delay in both the high level as well as detailed implementation remain same; the increasing trend for delay has been observed with the increase in polling intervals as in both the cases, the packet would be transmitted when the poll would take place.

In light of the above results, it has been observed that the trends for energy consumption and delay in ADP-MAC differ between theoretical simulations and testbed experiments (low-level simulation). This finding highlights the need for caution when relying solely on simulation studies for real-world application implementation. It is possible that discrepancies arise due to factors such as potential bugs in the simulation program, limitations in the analytical model (e.g., not accounting for all energy consumption factors), or differences in implementation quality that may not have been captured in the simulations. Testbed-level studies, on the other hand, incorporate real-world scenarios, including hardware malfunctions and network dynamics, which theoretical simulations cannot fully replicate. Thus, researchers are encouraged to conduct both simulation and testbed experiments to validate their network protocols and ensure robust real-world performance.

V. LIMITATIONS AND CONSTRAINTS

Based on the experimental setup, results, and evaluations, several limitations, boundaries, and constraints were identified. First, the high-level MATLAB simulations rely on several assumptions, such as fixed energy consumption values and simplified channel conditions, which may not reflect real-world scenarios, leading to discrepancies in the results when compared with detailed testbed implementations. Additionally, the lack of modeling preamble transmissions, collisions, and retransmissions in the MATLAB implementation led to unexpected energy consumption trends when applied to the Mica2 motes using TinyOS and Avrora. Furthermore, the use of an emulator (Avrora) instead of a physical testbed introduces limitations in capturing real-world sensor network dynamics, such as hardware malfunctions and environmental factors, which can influence the overall system performance. While the study used a reasonable range of assumptions and experimental setups, scalability to larger networks and diverse environmental conditions remains a boundary that should be explored in future work. Finally, the trade-offs between energy consumption and delay observed in the testbed implementation suggest that different network configurations may produce different results, highlighting the need for context-specific protocol adjustments.

VI. CONCLUSION AND FUTURE WORK

This paper presented the results of performance evaluation conducted for an adaptive and dynamic MAC protocol (ADP-MAC). The authors initially conducted high-level simulation for the protocol using MATLAB, whereas the detailed implementation was developed at a later stage using Mica2 platform and Avrora simulator. Significant differences were observed in the trends of energy and delay when the two simulation results are compared. The rationale behind these differences in trends for the two simulation levels reveals that the high-level simulations may not reveal the true performance of the protocols as various predictions/assumptions do not remain valid for the full implementation. Also, it is not possible to model all the attributes of physical layer in the high-level simulations. For example, while conducting the initial study, the concepts of channel access delays and packet collisions could not be modeled. Based on these findings, it is suggested that the proposed protocols should be implemented to the node level in order to reflect close to real performance.

In future, we plan to implement ADP-MAC in large-scale, real-world testbeds to evaluate its performance under diverse network conditions and traffic scenarios. Moreover, we also aim to explore enhancements that address challenges such as heterogenous traffic management, potentially through emerging machine learning-based optimization techniques.

ACKNOWLEDGMENT

This contribution is supported by HORIZON-MSCA-2022-SE-01-01 project COALESCE under Grant Number 10113073.

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Delay Management Using Packet Fragmentation in Wireless Industrial Automation Systems

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***Abstract*—Managing delay is one of the core requirements of industrial automation applications due to the high risk associated for equipment and human lives. Using efficient Media Access Control (MAC) schemes guarantees the timely transmission of critical data, particularly in the industrial environments where heterogeneous data is inherently expected. This paper compares the performance of Fragmentation based MAC (FROG-MAC) against Fuzzy Priority Scheduling based MAC (FPS-MAC), both of which have been designed to optimize the performance of heterogenous wireless networks. Contiki has been used as a simulation platform and a single hop star topology has been assumed to resemble the industrial environment. It has been shown that FROG-MAC has the potential to outperform FPS-MAC in terms of energy efficiency and delay both, due to its inherent feature of interrupting ongoing lower priority transmission on the channel.**

Keywords—industrial IoT; FROG-MAC; fragmentation; priority

I. INTRODUCTION

In the context of modern industrial automation and control systems, advanced technologies, such as wireless communication, artificial intelligence, big data analytics, digital twins and blockchains have played a pivotal role. The advent of Industry 4.0 and Industrial Internet of Things (IoT) has ushered in countless opportunities for enhancing industrial output by minimizing malfunctions and reducing downtime [1]. Amidst these advancements, managing heterogeneous traffic emerges as a core challenge for wireless industrial automation systems, demanding efficient handling of prioritized traffic streams. As industries strive for seamless operations and optimized performance, addressing this challenge becomes imperative to ensure the smooth functioning of critical processes and systems [2]. Hence, exploring innovative techniques for delay management becomes increasingly significant for industrial wireless networks.

For the wireless communication, delay management can be implemented at various layers of communication stack. Since MAC layer plays a vital role in scheduling of packets, it has been one of the hottest areas of interest of past researchers to develop priority mechanisms [3]. Some of the major techniques proposed for ensuring quick delivery of high priority data include adaptive contention windows [3], queue management [4], adaptive data rate adjustment [5], duty-cycle adaptation [6], wake-up radio [6] and multi-channel usage [8]. Also, various hybrid schemes have been proposed, which combine some of the advanced techniques along with using conventional super-frame method [9] and Time Division Multiple Access (TDMA). Although most of these techniques guarantee a prioritized channel access for high priority traffic, if the lower priority traffic has already started to transmit, it is no longer possible for the higher priority traffic to interrupt the ongoing transmission. Moreover, for the super-frame based protocols which claim slot-stealing, stealing is only possible until the transmission is scheduled, not yet begun [9].

In industrial settings, wireless sensors may generate heterogeneous traffic of varying priorities in several applications. For example, wireless sensors deployed to monitor the health and performance of machinery may generate heterogeneous traffic. Critical equipment, such as turbines or pumps, might require real-time monitoring and immediate response to prevent breakdowns, while less critical equipment may have lower priority traffic for periodic status updates. Similarly, industrial facilities often utilize wireless sensors to monitor environmental conditions, such as temperature, humidity, and air quality. Certain parameters, like temperature in a furnace or chemical concentration in a storage tank, may require immediate attention in case of deviations, while others, such as ambient humidity, may have lower priority. Moreover, wireless sensors used for safety and security purposes, such as fire detection systems, intrusion alarms, or access control systems also generate heterogeneous traffic [11]. Critical events like fire or unauthorized access may require immediate notification and action, while routine security checks may have lower priority. Clearly, most of the mentioned scenarios represent an emergency and it is not practical for the urgent data generated during this to wait for the completion of ongoing transmission on the network, if any.

In this work, we advocate for the usage of packet fragmentation scheme, FROG-MAC [10] for the industrial automation system. FROG-MAC is a MAC protocol which has specifically been designed for prioritized heterogenous traffic and can be used for a wide range of applications, such as wireless body area networks, vehicular ad hoc networks and industrial networks. In this protocol, the traffic of varying priority attains a varying level of channel access. The higher priority traffic gets an immediate access through interrupting the ongoing transmission of lower priority packets. This is ensured by transmitting the lower priority packets in the form of short fragments, while the higher priority traffic is always transmitted as a single unit. Further details of FROG-MAC's operation will fall later in the paper. We compare the performance of FROG-MAC with FPS-MAC (which is a fuzzy priority scheduling based MAC) in this work, specifically for industrial sensor systems.

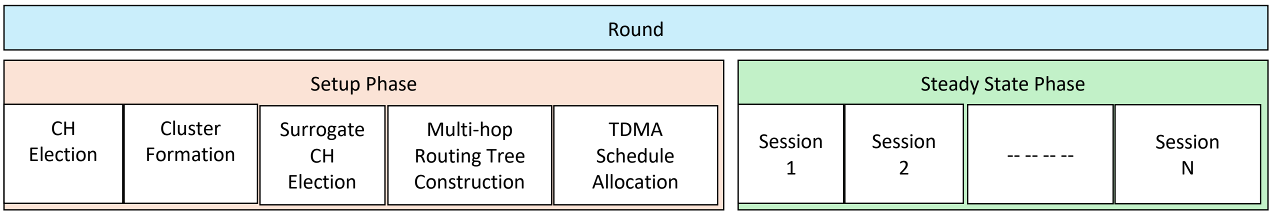

Figure 1: Operation Phases of FPS-MAC [11]

Rest of this paper has been organized as follows: Section II summarizes the relevant work; section III presents the experimental settings; section IV details the results and discussion and finally, section VI concludes the work and suggests future work directions.

II. RELEVANT WORK

In this section, we present a brief overview of FPS-MAC and FROG-MAC, the two protocol which have been compared for their performance in terms of latency for the industrial sensor networks. FPS-MAC works on the principles of slot stealing and fuzzy based scheduling, whereas the core concept of FROG-MAC is data fragmentation.

FPS-MAC has been designed to steal the data slots from periodic traffic in order to transmit the higher priority data first [11]. This way, fuzzy priority scheduling is done in the event-based scenarios to guarantee the timely access for emergency traffic and also, to ensure the appropriate level of Quality of Service (QoS). FPS-MAC operates in two phases of set-up and steady state phase, as shown in Figure 1. In the setup phase, the Cluster Head (CH) selection and cluster formation take place. To ensure that each cluster remains operational even after the failure of Master Cluster Head (MCH), the surrogate CH election is also conducted. Moreover, the routing tree is created and TDMA schedule is allocated. Subsequently, both the intra- and inter-cluster data transmission takes place during the steady state phase. As shown in Figure 2, TDMA frames are differently designed to manage the periodic monitoring and emergency situations.

For the event situation, the Emergency Indication Slot (EIS slot) is used, where the nodes having some urgent data indicate the channel requirement. These nodes must listen for the EIS period, and if they find the channel idle, they can begin transmitting the indication signal. Here, there are two possible transmitter nodes for the indication signal; a node which has just detected an event, or a node which has to transmit previously buffered event traffic. The CH then acknowledges the indication signal and switches the transmission mode from periodic to emergency; this is followed by the control period during which all the member nodes remain active in order to obtain information about the current TDMA frame. Later, there are some operational differences for the frames as shown in Figures 2 (a) and (b), based on whether the protocol has to deal with routine or emergency traffic. Fuzzy based scheduling is another major contribution of FPS-MAC, where the priority level of each node is computed using information about "intra-cluster distance (distance between member node and Cluster Head (CH))," "residual energy," "slots required," and "emergency bit".

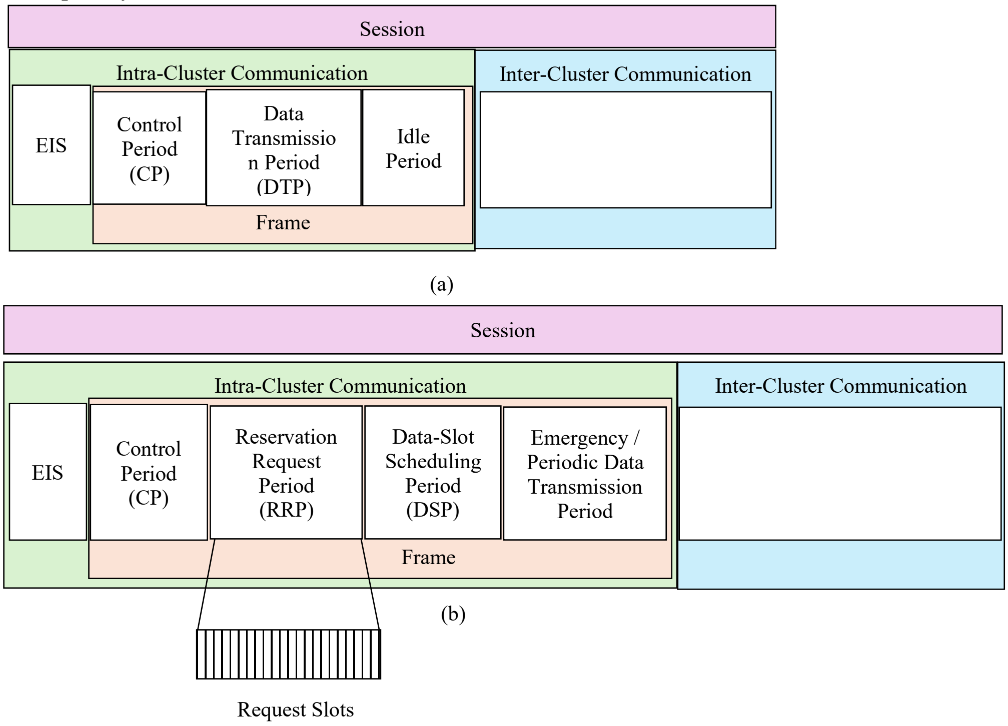

Figure 2: TDMA Frame Format for FPS-MAC- (A) Periodic Transmission, (B) Event Situation [11]

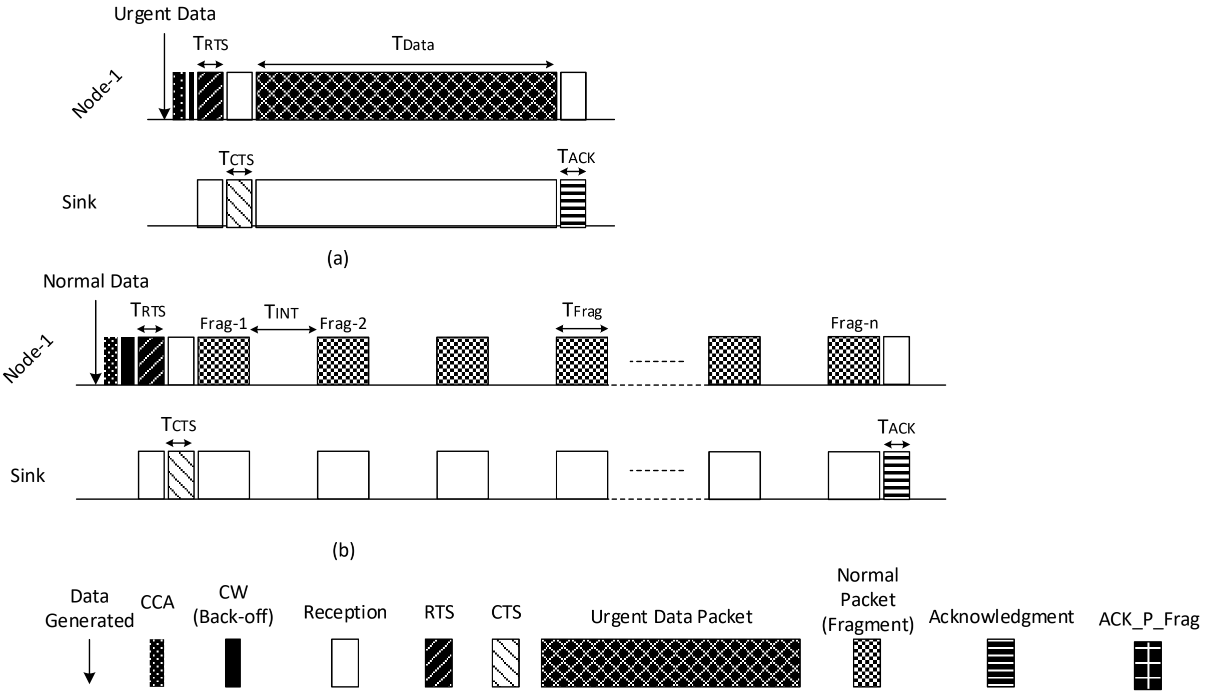

Figure 3: Basic Operation of FROG-MAC [13]

FROG-MAC [10] is an asynchronous MAC protocol where the operation has been defined on the basis of heterogenous priority data. FROG-MAC introduced a groundbreaking technique: the ability to interrupt ongoing transmissions on the channel—a feat previously unattainable with existing MAC schemes, despite the development of numerous priority-based MAC protocols tailored for mission-critical applications [12]. The basic operation of FROG-MAC is shown in Figure 3, where the low priority data transmission is done in fragments (Figure 3a), and high priority data is sent as a single packet (Figure 3b). The pauses between fragment transmissions allow the data of emergency nature to request and obtain channel access quicker, as compared to if had to wait for the complete transmission of ongoing lower priority data.

III. EXPERIMENTAL SETUP

The experiments are performed for testing the service provided to two levels of services generated by the nodes in a single hop network, emergency and normal. The emergency traffic represents data of time-critical and unpredictable nature such as fire occurrence or gas leakage. On the other hand, normal data represents the packets periodically generated to communicate the health and state of plants/equipment; this category of traffic will include examples of temperature and humidity data.

20 nodes were set in a star topology, whereas 21st node acted as the cluster head/sink. The number of nodes sending emergency traffic varied between 3 and 18 assuming the spread of event, and its detection by various nodes; similar assumption has been made in [11], where it is stated that in the case of fire occurrence, various nodes will continue to detect and report as the fire spreads. Star topology is used in this paper, assuming that all the nodes will be reporting emergency event to their cluster head. However, for more complex topologies, such as linear multi-hop, experiments can be performed using multi-priority data, where fragmentation would be valuable for reducing the delay.

TABLE I. SIMULATION SETTINGS

Simulation Parameter	Simulation Settings
Simulation Area	50 X 50 m
Simulation Duration	5000 Sec
Total Number of Nodes	21
Number of Transmitting nodes	Variable
Message Generation Interval of Urgent/Emergency/Event-detection Traffic	2 min
Message Generation Interval of Normal/Periodic Traffic	10 sec
Data Packet Length	34 Bytes
Fragment Size for FROG-MAC	Varying (2 to 32)

For simulating the FPS-MAC, the nodes used dynamic TDMA based scheme as discussed earlier, whereas fragmentation was implemented on the normal data for simulating FROG-MAC. Other simulation settings used for the present study are shown in Table 1.

IV. RESULTS AND DISCUSSION

The delay performance comparison of FPS-MAC and FROG-MAC has been illustrated in Figure 4, by varying the fragment size. For FPS-MAC, the delay has been higher as compared to FROG-MAC because of the underlying differences in the TDMA-based and asynchronous protocols. In FPS-MAC, the lower priority nodes have to wait for their allocated slot for transmission, which could be few sessions away; same is the case for event-detecting nodes, which might not always get the channel access

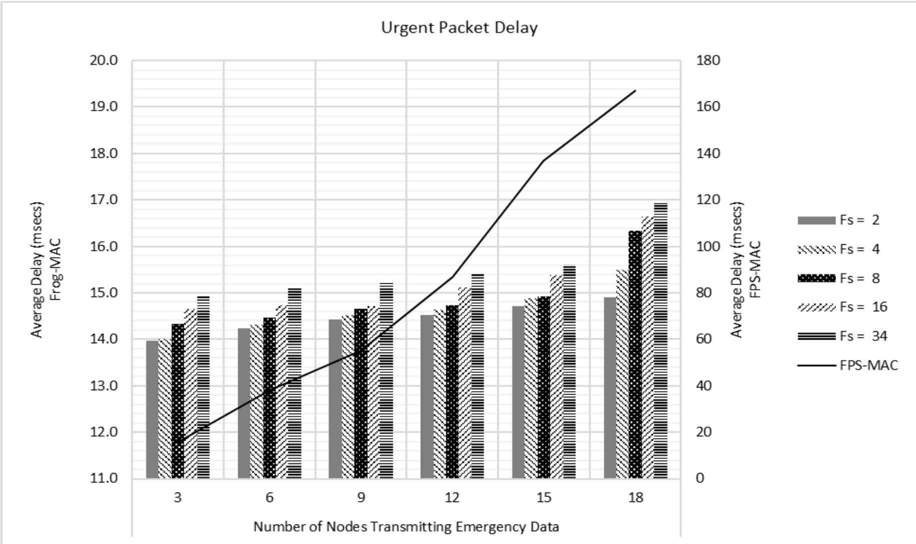

Figure 4: Average Delay Comparison of FROG-MAC and FPS-MAC by Varying Number of Transmitting Nodes and Fragment Size

during their first attempt during EIS period. On the other hand, in FROG-MAC, the nodes get a chance to transmit without waiting for the typical handshaking being performed in the FPS-MAC (the schedule information communication between the CH and each node). For the FROG-MAC, there is a slight difference in delay when number of fragments are increased; this is because of the possibility of interruption by higher priority traffic during the transmission, and also because of the additional header bytes that will be sent along with the excessive fragment transmissions.

Next, the delay performance is compared for the emergency/urgent traffic by varying the number of nodes that send urgent data; the results have been shown in Figure 5; here, the fragment size for FROG-MAC was chosen as 8 bytes. For the increasing number of nodes, the delay is shown to be rising for both protocols, as there will be a higher contention between event-detecting nodes. However, since the waiting time is much lower for FROG-MAC, we see a significant difference in the delay results. Firstly, the nodes operating with FROG-MAC do not have to wait for the EIS; secondly, there is even a possibility of getting channel busy during EIS for FPS-MAC; thirdly, once a node sends an indication message during EIS, it has to wait for its turn; there could also be a probability that it does not receive an acknowledgement from the CH, which would imply that the node might have to wait for another EIS period despite having won the channel in the first attempt. On the other hand, the nodes in FROG-MAC only have to wait for the short fragment being transmitted on the channel; as soon as it is done, the nodes which detect event could quickly grasp the channel and send their data. Finally, the priority assignment in FPS-MAC is done based on the fuzzy algorithm, which might not always result in true representation of emergency identification. On the other hand, for now, the FROG-MAC has been assigned well-defined static priorities which would ensure that higher priority nodes always get access to channel by interrupting the lower priority data.

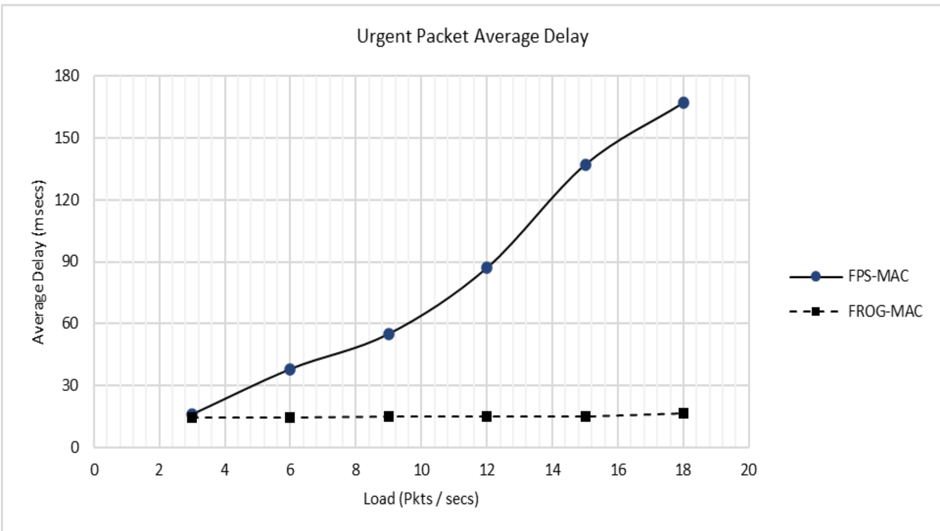

Figure 5: Average Delay Comparison of FROG-MAC and FPS-MAC by Varying Traffic Load

V. Conclusion and Future Work

We presented a performance comparison of MAC protocols designed for dealing with prioritized heterogenous traffic, which is common in industrial environment today. We chose FPS-MAC, where the nodes steal slots for facilitating the higher priority traffic, and FROG-MAC where the lower priority data is fragmented in order to provide early channel access to the urgent traffic. We varied the number of nodes transmitting urgent data and overall traffic load to represent the industrial data, and compare the 2 protocols. Moreover, the impact of fragmentation has also been illustrated. It has been found that FROG-MAC outperforms FPS-MAC in terms of latency, due to providing the chance of interruption of ongoing transmission, which is not possible in the operation of FPS-MAC.

In future, we plan to enhance the functionality of FROG-MAC by integrating it with the machine learning algorithms. The protocol will be designed to learn from the previous operational cycles so the optimal fragment size could be decided for each type of traffic. This would ensure achieving an even higher level of performance. Moreover, we also plan to focus on enhancing the reliability and robustness of FROG-MAC to ensure uninterrupted communication in challenging industrial environments. This includes mitigating packet loss, minimizing interference, and implementing error detection and correction mechanisms to maintain data integrity and reliability under adverse conditions. Also, FROG-MAC will be compared with standard protocols for various applications, such as with IEEE 802.11-p for vehicular networks.

Acknowledgment

This contribution is supported by HORIZON-MSCA-2022-SE-01-01 project COALESCE under Grant Number 10113073.

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