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A roadmap to developing energy-efficient MAC protocol in wireless sensor networks: a case of ADP-MAC development and implementation

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SCP-MAC

T-AAD

ABSTRACT

Over the past two decades, hundreds of protocols have been developed for diversified applications of WSN corresponding to different layers in the communication stack. Among these, Media Access Control (MAC) layer protocols are of great interest due to providing possibility of optimizing performance parameters. Despite availability of a large number of survey articles, there remains a gap for a tutorial that offers guidelines about the development process of MAC protocol. In this paper, we present a detailed tutorial for developing a MAC protocol starting from the stage of research gap identification and ending at the performance evaluation. We described the journey of development and implementation of a novel asynchronous MAC protocol ADP-MAC (Adaptive and Dynamic Polling MAC) as a case study. ADP-MAC was developed by deploying a novel concept of channel polling interval distributions, and was compared against Synchronized Channel Polling- MAC (SCP-MAC) and lightweight Traffic Auto-Adaptation based MAC (T-AAD). Finally, we proposed major milestones of protocol development along with recommendations about publishing the research.

1. Introduction

Despite hundreds of MAC protocols having been developed and implemented for Wireless Sensor Networks (WSNs) over the past two decades, researchers continue to propose customized protocols for specific WSN applications. The development of MAC protocols has witnessed enormous growth due to the rapidly evolving applications of WSN and their integration with Internet of Things (IoT) [1]. Each emerging application area such as smart agriculture [2], smart transportation [3], smart energy [4], smart factory [5], Unmanned Aerial Vehicles [6], fitness tracking [7], and generic healthcare [8] requires a specific MAC protocol which well matches the requirements. Researchers, therefore, continue to design new protocols due to the lack of available standard which is well suited for the diverse range of applications [9].

Due to the rich diversity of WSN applications and available MAC solutions [10, 11], researchers often find it a challenge to begin working in the domain. None of the past studies have provided a roadmap for the extensive journey of developing a MAC protocol.

Although, the MAC protocols are very diverse in nature, a detailed plan focusing on their design, development and implementation will enhance the body of existing literature. In this context, we believe, the researchers need to follow a systematic approach to analyse the previous schemes and identify the unique challenges and research gap in the existing MAC solutions [12]. Once the gap is identified, the researchers should focus on either improving an existing MAC protocol or designing a new one from scratch. In either case, we suggest that a proof of concept must be developed as the first step and subsequently, protocol's features should gradually be added in the design.

Most of the times, it becomes troublesome for researchers to develop and implement a protocol as they tend to begin implementing all the complex features simultaneously. To avoid this difficulty, we suggest that initially, a high-level proof of concept should be developed and evaluated. At this stage, it is recommended that a simple to learn and use simulation tool such as MATLAB could be used. Subsequently, the advanced features of protocols should be added and implemented using more sophisticated simulation/testbed tools. Finally, the performance evaluation should be conducted by comparing with state-of-the-art protocols. In this work, we briefly outline the process of developing a MAC protocol for WSN in the light of our experience of developing Adaptive and Dynamic Polling-MAC (ADP-MAC) [13]. We also highlight the stages of protocol development at which the work can be published.

The major contributions of this article are listed below.

1. To provide a roadmap for description of the phases for systematic development of a MAC protocol.
2. To provide a guideline on identifying the research gap by conducting literature survey while considering appropriate inclusion and exclusion criteria.
3. To propose a protocol development methodology that starts from building a proof-of-concept and subsequently integrates complex features into the basic architecture.
4. To offer an insight into performance evaluation methods for the developed MAC protocol

Rest of this paper has been organized as follows: Section 2 presents a brief review of existing literature; section 3 describes the proposed roadmap by illustrating a flow diagram that begins with research gap identification and ends at comparing high level preliminary results with the detailed results. Section 4 describes the results by explaining how each milestone of protocol development should be achieved. For each milestone, examples have been taken from the experience of developing ADP-MAC. Finally, section 5 concludes the work.

2. Relevant Work

Due to the diversity of WSN applications, a wide range of MAC protocols has been found in the existing literature. These protocols are often categorized based on the applications, channel access mechanisms, channel polling methods, usage of cognitive radio, synchronization schemes and use of single or multi channels, etc. [14]. Moreover, these protocols are also often classified based on their design goal such as to achieve efficiency in terms of either delay, energy, reliability, or a combination of all.

While conducting literature search for this article, numerous relevant survey articles are found. For example, a survey of MAC protocols developed for acoustic under-water networks has been presented in [15]; application specific MAC protocols have been surveyed in [16, 17]; a wide array of scheduling and adaptive listening schemes deployed in MAC protocols have been surveyed in [18]; evolution of MAC protocols in terms of energy efficiency has been described in [19, 20]; a survey of QoS energy efficient protocols has been presented in [21] and time-critical protocols are reviewed in [22, 23]; context-aware delay tolerant protocols are reviewed in [24]; duty-cycling based protocols are discussed in [25]; protocols based on recent technique of energy harvesting have been surveyed in [26, 27] and those using receiver-initiated mechanism in integration with energy harvesting have been discussed in [28]; wakeup radio based protocols are described in [29]; opportunistic routing based MAC protocols are reviewed in [30]; mobility based protocols have been surveyed in [31]; MAC protocols based on traffic prioritization mechanism have been categorized in [32]; full duplex MAC protocols have been reviewed in [33] and survey of multi-channel protocols has been presented in [34, 35].

In addition to the survey of existing MAC protocols, some relevant tutorials and frameworks are also found. In [36], the authors presented a detailed methodology on conducting performance evaluation of low power lossy networks; similarly, another approach for performance evaluation of green MAC protocol has been proposed in [37]. A conceptual framework for developing future energy efficient MAC protocols has been developed in

[38]. A case study of MAC protocol to achieve lifetime maximization has been presented in [39]. A Markov model for investigating the 802.15.4 parameters has been proposed in [40]; this model is clearly only valid for theoretical performance evaluation of the protocols, rather than focusing on testbed or simulation environments. A framework for energy optimization using cross-layer scheme has been presented in [41]. Also, a guideline for selecting simulation tools for WSN has been provided in [42], but this study lacks the roadmap for protocol design. Research issues and challenges faced by IoT and WSN have been detailed in [43], and challenges related to cross-layer design along with the possible solutions have been presented in [44]; however, step-wise methodology for developing a MAC protocol that could address the relevant challenges has not been provided.

The above review of past works establishes that there has been no detailed tutorial published for developing a MAC protocol. Instead, the focus of articles has been on providing the researchers with a rich classification of protocols, whereas, the development process is left onto them. Hence, there remains a gap for providing an insight for the complete process starting at the idea conception and ending at the performance evaluation of new MAC protocol.

3. Proposed Roadmap

The major milestones (M1-M5) a researcher needs to cover during the journey of MAC protocol development are detailed in Fig. 1. The figure also marks stages (P1-P5) at which the work in progress can be converted into research articles for publication. Each of these milestones/stages are discussed in detail later in the paper by exemplifying the development of ADP-MAC.

4. Results and Discussions

In this section, we describe each stage shown in Fig 1. The guidelines for each of these phases have been provided considering the development experience of ADP-MAC.

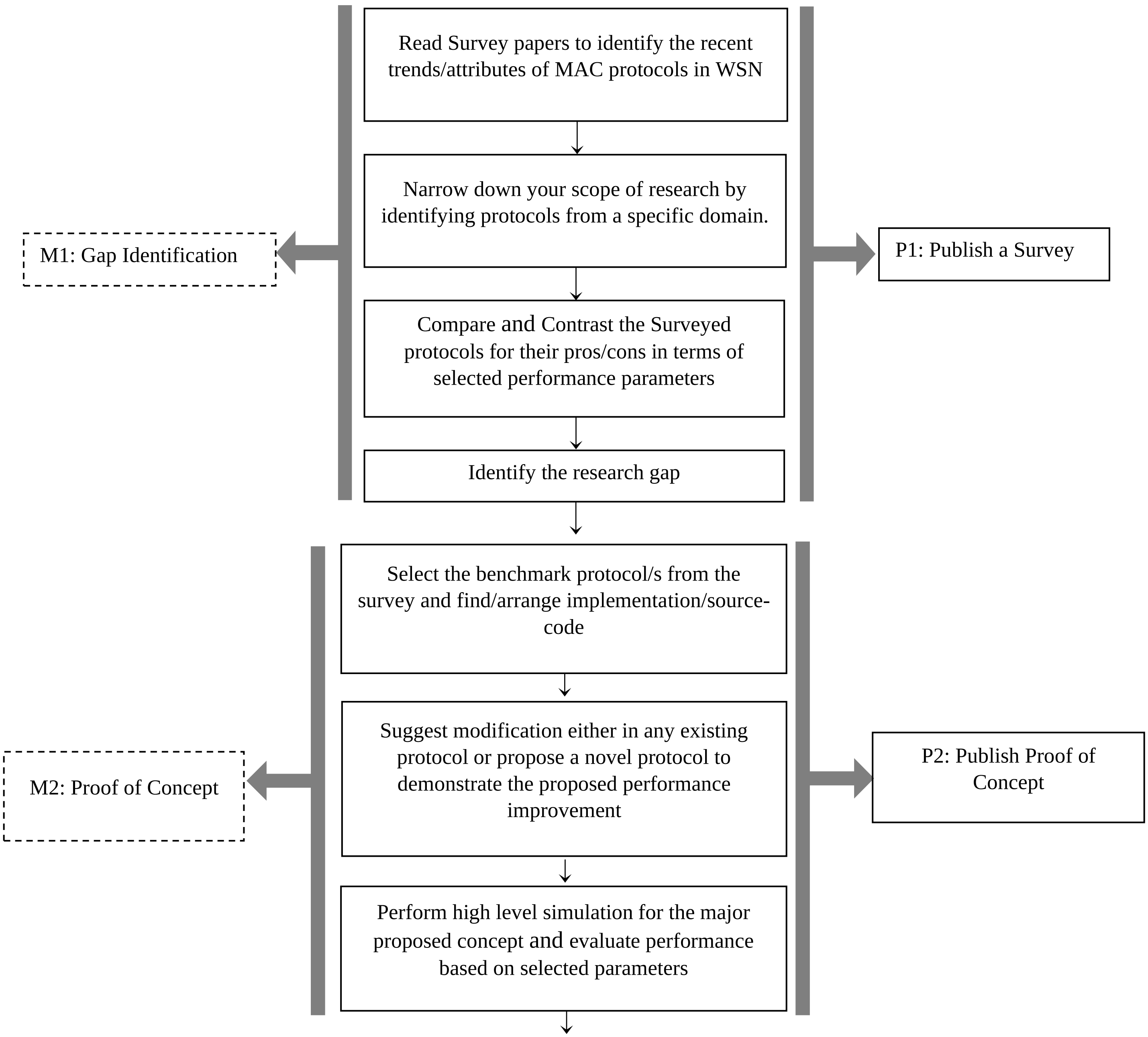
4.1 M1: Gap Identification

As indicated in Fig. 1, the first milestone will be achieved by conducting an in-depth literature survey and identifying the research gap. This requires the researcher to thoroughly read the survey articles which provide an insight about the latest and historical trends of MAC protocols development. Subsequently, several protocols from survey articles must be selected and detailed study for each has to be conducted. Appropriate keywords should be used to extract articles from efficient and reputed search engines such as Google Scholar. It is also important to note that the major chunk of sources used should have been published within last 10 years, and top journal articles from the domain should be given a priority. The journals must be identified from Journal Citation Reports (JCR) or Master Journal List (MJL). For wireless networking and sensing domain, the journals such as IEEE Sensors, IEEE Transactions on Wireless Communications, IEEE Communications Surveys and Tutorials and ACM Transactions on Sensor Networks are some examples of most reputed journals. If needed, the proceedings of top conferences may also be included in the survey. For the domain of wireless sensor networks, IEEE International Conference on Communications (ICC), IEEE International Conference on Computer Communications (Infocom), ACM Conference on Embedded Networked Sensor Systems (SenSys) and IEEE Global Communications Conference are considered to be top tier. Thus, the articles which have not been published in top-tier journals or conferences within last 10 years must be excluded from the survey.

During our study, we conducted a comprehensive survey of MAC protocols which were published from 2005 onwards, using Google Scholar and the digital library of our university. We used the keywords "asynchronous MAC protocols", "synchronous MAC protocols", "polling-based MAC", "dynamic polling", "adaptive polling", "polling distributions" and "polling interval distributions". To have a comprehensive overview of the previous work done in the field, we reviewed several survey articles highlighting MAC protocols developed for various applications in WSN; these articles also helped us to identify the existing challenges [12, 45-50]. Moreover, the major protocol, SCP-MAC, that was selected for developing ADP-MAC had been published in ACM Sensys. Thus, we considered the above detailed inclusion and exclusion criteria.

As seen in section 2, it was observed that reducing energy consumption for WSN had been of major researchers' interest and various approaches had been adopted for the purpose [12, 51-53]. Also, asynchronous MAC protocols had proved to outperform the synchronous protocols in terms of energy consumption [12, 54-57]. Therefore, after spending some time in analysing the energy efficient MAC protocols, we found it interesting to work on the concept of dynamic channel polling. We opted to design ADP-MAC based on dynamic polling because for the real-life applications of

WSN, there are often the cases where we may need to optimize delay or energy. For example, we may consider the intrusion detection application; when an intrusion occurs and burst is sent, the delay cannot be tolerated whereas energy efficiency could be compromised. In contrast, when no intrusion occurs, and the network just sends information packets, the goal is to increase overall network lifetime by reducing energy consumption, while the delay can be tolerated.



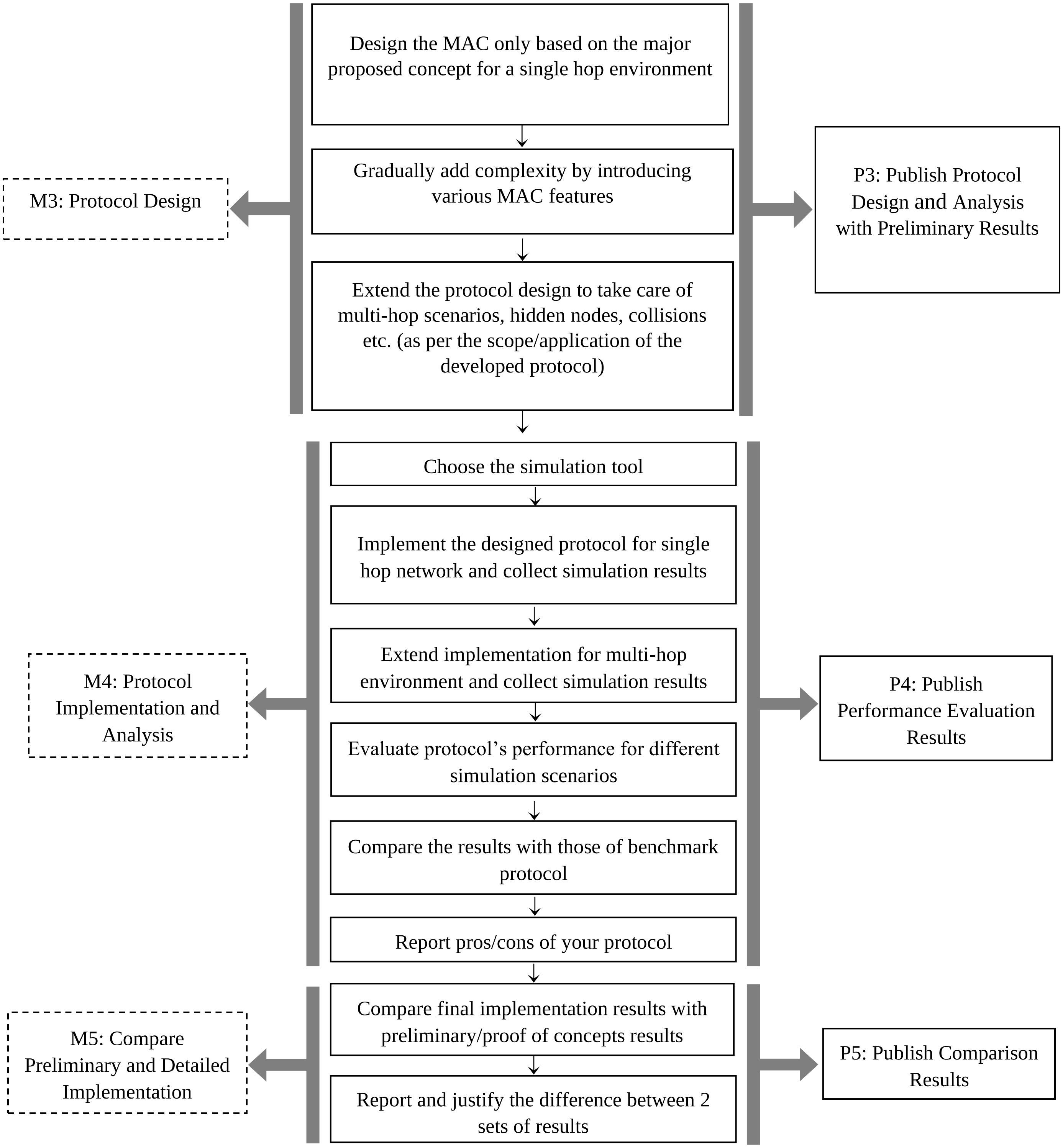


Fig. 1. Milestones for developing a MAC protocol for WSN

We began by studying MAC protocols which primarily introduced the concepts of channel polling [58] and subsequently narrowed down the research to dynamic polling-based protocols. Meanwhile, we also ensured the availability of source code of the protocols, as we had to select the benchmark protocol to compare the performance of our proposed protocol. Finally, we were able to identify SCP-MAC (Synchronized Channel Polling-MAC) [59] as a benchmark protocol as it was directly relevant to the selected concept and its open-source implementation was also available [60].

While studying SCP-MAC in detail, it was revealed that many gaps existed in the protocol in the context of energy-efficient channel polling. The major contribution of SCP-MAC was to combine the features of synchronous and asynchronous protocols for introducing the concept of 'Synchronized Channel Polling' [59]. The nodes in SCP-MAC wakeup at loosely synchronized schedules which not only eliminates the need of sending synchronization packets in every cycle, but also considerably reduced the length of preambles as compared to the previous asynchronous protocols such as WiseMAC [61] and B-MAC [58]. Although SCP-MAC deployed scheme of adaptive polling as shown in Fig. 2, it was not very efficient. In cases where a packet is received during a regular channel poll, the node adaptively polls the channel several times before going to sleep. This increased the probability of receiving the packets earlier as compared to if the node had only woken up in the next cycle. However, the proposed adaptive polling strategy lacked efficiency in the following ways: firstly, in the case where no packet is found in the adaptive polls, the energy of these polls got wasted and secondly, the packet would still have to face delay if it is generated right after all the adaptive polls had taken place. Therefore, despite wasting energy in the adaptive polls, there was a considerable probability that the packets would face a high delay. This analysis led us to consider deploying ‘polling interval distribution’ instead of only adjusting the ‘polling intervals’ of nodes.

We initially hypothesized that instead of using adaptive polling as in SCP-MAC, use of polling interval distribution would lead to better results in terms of energy and delay. We also decided to analyse the incoming traffic arrival patterns and select the polling interval distributions accordingly, rather than using a single polling distribution for all traffic patterns. Hence, we mainly proposed the concept of adaptive and dynamic channel polling which refers to using a specific interval distribution based on the analysis of co-efficient

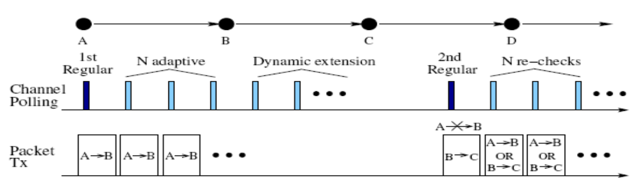


Fig. 2. Adaptive channel polling proposed by SCP-MAC [52]

4.2 M2: Developing Proof of Concept

Before beginning the detailed protocol design, we advise the researchers to develop a proof of concept. This would help to gain confidence that the basic proposed idea is sound enough to serve as a foundation for novel MAC protocol. As previously mentioned, we planned to develop a MAC protocol based on the concept of polling interval distributions; hence, we conducted a preliminary study to present the proof of concept before

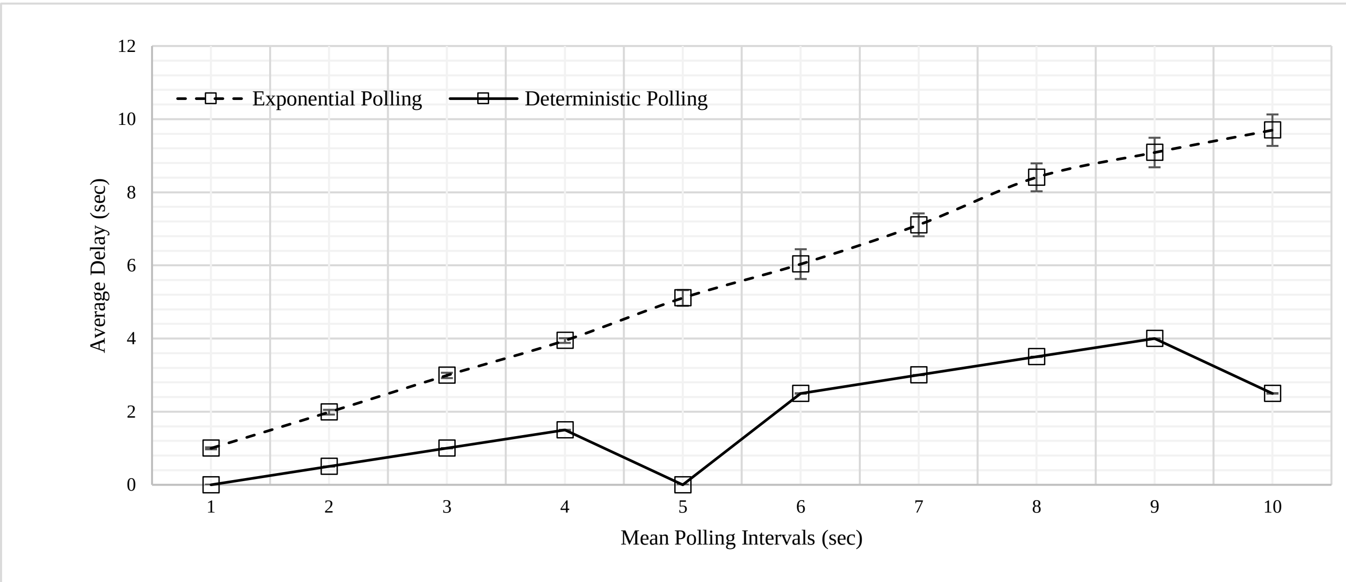
of variation (Cv) of the incoming traffic pattern. Cv has been recommended for a better insight about the incoming data [62]. The details of calculating Cv and integrating it with the protocol ADP-MAC have been presented in [13].

To validate the research gap, we surveyed the recent protocols again and it was established that no previous MAC protocol had been developed based on the concept of ‘polling interval distributions’. Previous researchers had proposed protocols based on the history of traffic patterns, but those protocols mostly suggested the polling intervals, such as AX-MAC [63], Boost-MAC [64] and AS-MAC [56]. Hence, we identified the research gap to develop a protocol based on analysis of traffic arrival patterns and subsequent dynamic switching of ‘polling interval distributions’.

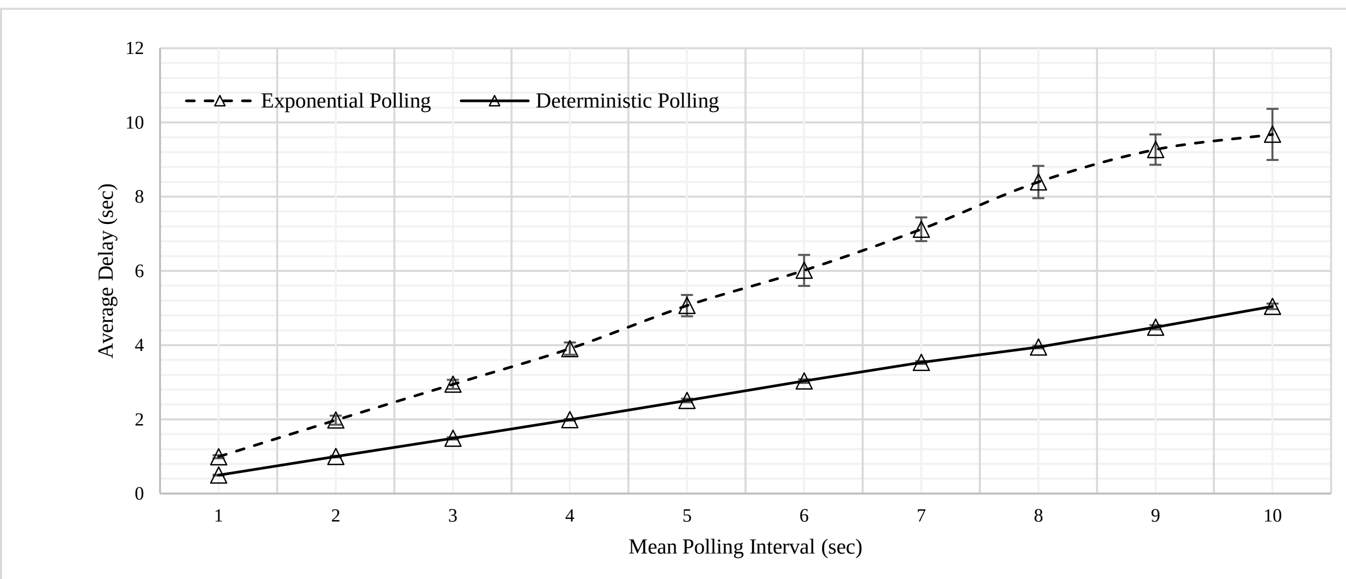
While studying the existing protocols for analysing different schemes/approaches taken for channel polling, other features such as packet concatenation and block acknowledgement transmission were also found interesting. Both techniques were reported to improve the performance of WSN through reducing the packet overhead and hence, improving the energy performance [65-67]. Therefore, we included the relevant papers in our survey. However, since we planned to only partially implement these supplementary features, we only studied and analysed few schemes to identify the best approach for integrating them with ADP-MAC. At the end of literature survey, we were able to publish 2 surveys: the first was based on our analysis of existing channel polling mechanisms in WSN [68] and the other was based on the analysis of previous data aggregation techniques [69].

designing and implementing ADP-MAC. Since the protocol design was not ready at this stage, we conducted a high-level simulation using MATLAB. As We already knew the parameters of interest (energy and delay), we made assumptions about the packet sizes, energy consumed in different activities etc. We tried to keep the assumptions as realistic as possible by considering the parameter settings of previous published protocols, particularly those of SCP-MAC [60].

We performed simulations for two types of arrival and polling distributions: deterministic and exponential. The arrival patterns were assumed considering the most common applications of WSN, as had been selected by previous authors [70-73]. The focus of simulations in this phase was on assessing the role of exponentially distributed polling intervals for each type of arrival process, without including other MAC details. The preliminary results proved that in case exponentially distributed polling intervals were used for each arrival distribution, energy consumption reduced, whereas transmission delay increased. In contrast, when deterministic polling process was used for both arrival distributions, it was found that the delay reduced but the energy consumption increased; hence a trade-off between two parameters was found upon comparing deterministic and exponential polling processes. These results were published in [74] and delay plots have been shown in Fig. 3. Thus, it was proved that the proposal of using polling interval distributions can be beneficial in terms of energy efficiency for WSN.



(a)



(b)

Fig. 3: High level simulation results for performance evaluation of polling interval distributions (a) CBR arrivals (b) Poisson arrivals

In addition to the implementation-based approach we have taken to evaluate our proposal of switching polling interval distribution, researchers may also opt for performing analytical modelling and evaluation. A number of authors have recently conducted statistical analysis of their protocols prior to implementing their ideas, such as [75-77].

4.3 M3: Designing the Protocol

The next milestone is to theoretically design the MAC protocol considering various transmission scenarios. At this stage, the researcher would need to identify the type and flow of packets that would be required for the protocol's operation in specific application scenarios. Therefore, after ensuring the benefit of our proposed concept (use of polling interval distributions), we began working on the protocol design. For simplicity of the design process, we initially assumed the single hop network of two nodes only, in order to avoid the possibility of parallel transmissions by other neighbours. The goal was to transmit data using the deterministic or exponential polling intervals. We finalized all the packets and their fields which were required for successful data delivery with the minimum packet overhead. At this stage, we named the protocol as PD-MAC (Probability Distribution-MAC), details and preliminary results of which were published in [78]. The chosen packet types were short preamble strobes, Early Ack (EA), Data (single or concatenated) and Ack. The idea of sending short preamble strobes instead of long preamble sequence was adopted from [79].

The design of PD-MAC was then extended by introducing dynamic polling intervals. As previously mentioned, our key idea was to be able to analyse the incoming traffic patterns so that the receiver nodes wake up precisely at the same instant when the data arrival is expected. We identified that statistical measure of co-efficient of variation [80] was the most appropriate for our requirements and hence it was used in ADP-MAC design. The protocol was then designed for the single and multi-hop scenarios and was named as ADP-MAC and published in [13].

In ADP-MAC, we studied three types of traffic: Constant-Bit-Rate (CBR), Poisson and Bursty (packets coming in at random intervals). These arrival patterns reflected the common WSN applications with dynamic arrivals [81]. ADP-MAC was developed to perform three types of polling: Deterministic (polling at constant intervals), Exponential (polling at exponentially distributed intervals) and Dynamic (polling at intervals selected based on the analysis of incoming traffic patterns). It is also to be noted that the work published in [13] did not include the features of packet concatenation and block acknowledgement, which were later published in [82] with detailed performance evaluation presented in [83]. Moreover, ADP-MAC was evaluated specifically for healthcare settings in [84] and for bursty traffic in [85]. As previously mentioned, we proposed the novel concept of using polling interval distributions, whereas dynamic duty-cycle was an established approach; therefore, we compared these two techniques and published the results in [86].

The brief operation of sender and receiver nodes in ADP-MAC has been illustrated in Fig. 4:

4.4 M4: Implementing and Analysing the Protocol

Once a MAC protocol is designed, it is crucial to test its performance in comparison to the existing solutions. Designing and implementing can be done in parallel, or whole protocol can be implemented at once after the design gets completed. We chose Tiny-OS for developing ADP-MAC and Avrora emulator for conducting simulations; the physical layer of SCP-MAC was used which was developed in nes-C (for Tiny-OS1 environment). Initially, we implemented ADP-MAC for single hop scenarios only, with the major concept of dynamic channel polling and then, included more nodes in the simulations. Subsequently, multi-hop scenarios were introduced in a linear topology. Gradually, we increased the complexity of source-code by making more nodes generate and forward the packets. Also, we changed the topology to grid after testing the implementation fully for the simple linear multi-hop topologies.

We performed simulations for comparing the performance of SCP-MAC and ADP-MAC in terms of delay, energy, and packet loss for Poisson, CBR and Bursty arrivals [8]. The critical simulation settings have been detailed in table 1; for the remaining experimental settings, the reader may refer to [13]. It was found that ADP-MAC was superior in performance for all the parameters, as shown for energy consumption and delay in Fig. 5.

In Fig. 5, SCP-MAC and ADP-MAC have been simulated for CBR (CA) and Poisson (PA) arrivals. Also, the three cases of ADP-MAC were simulated where ADP-MAC was limited to perform only deterministic polling (DP), only exponential polling (EP) and the dynamic polling (DyP). It has been observed that when there is a match between the type of polling and arrival distributions, the protocol performs better both in terms of energy and delay. For dynamic polling, the energy consumption and delay for each type of traffic is observed to be better than the cases when there was not a match between arrival and polling distributions; however, the energy and delay came out to be higher for dynamic polling as compared to the situations where there was a perfect match between the arrival and polling distributions. This finding revealed that the applications developers should select the polling interval distribution in line with the application requirements/expected arrival patterns. Finally, it has been found that for both the CA and PA, the performance of SCP-MAC was inferior to that of ADP-MAC in terms of both energy and delay. The major reason for better performance of ADP-MAC is the dynamic polling, absence of synchronization overhead and lesser idle listening and overhearing.

In addition to SCP-MAC, we also compared ADP-MAC with a protocol that was based on dynamic duty-cycling and lightweight Traffic Auto-Adaptation, T-AAD [87]. We proved that ADP-MAC outperformed T-AAD; this work was published in [86]. Simulation parameters used for comparing ADP-MAC with T-AAD are shown in table 2, whereas others were kept same as earlier listed in Table 1.

Fig. 6 illustrates the performance comparison of T-AAD and ADP-MAC. The energy consumption of T-AAD has been found to be the highest, whereas ADP-MAC with dynamic polling exhibited lowest energy consumption due to having a better match between traffic arrival and channel polling instants. As a result, lower number of preamble packets needed to be sent; moreover, lesser overhearing and idle listening occurred which saved the energy.

4.5 M5: Comparing Detailed Implementation with Preliminary Simulations

We also compared the results of preliminary proof-of-concept simulations with the full implementation. At this stage, the researchers should be able to identify the differences between the two sets of results and justify any differences. We performed a high-level comparison of the results published in [74] and [13] to have an insight about the differences/similarities in the expected and achieved results. The comparison showed that there was a contradiction between the expected and obtained results. In the preliminary results, it was seen that if deterministic polling is performed for any arrival distribution, delay reduces but the energy consumption remains high (as seen in Fig. 3). Furthermore, for the exponential polling, the preliminary findings suggested that the delay would increase, and the energy would reduce. In contrast, when the full protocol was implemented, it was revealed that exponential polling results in both better energy and delay performance as compared to the deterministic polling, as shown in Fig. 5.

Table 1

Simulation Settings for Comparing ADP-MAC with SCP-MAC

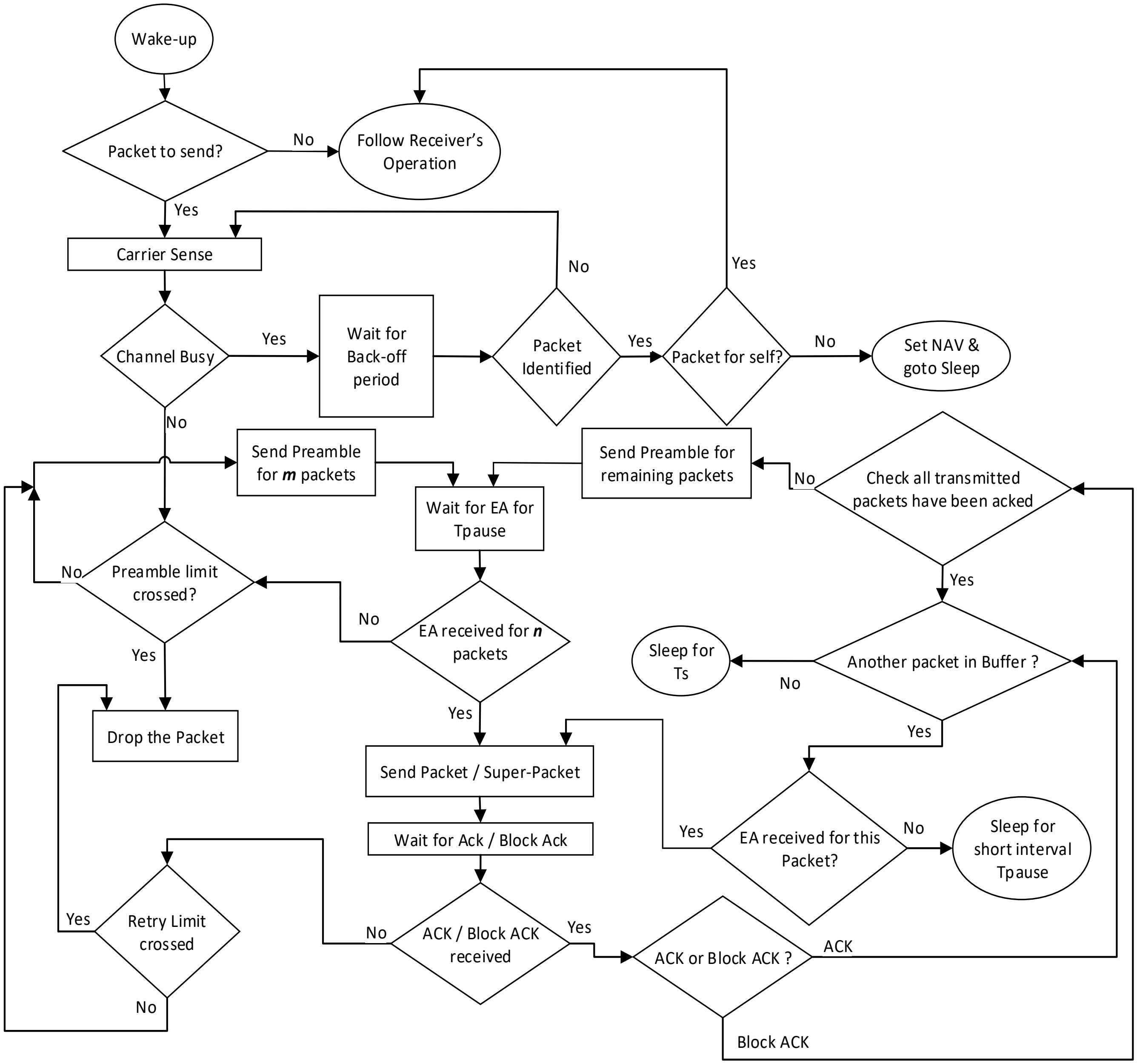
Simulation Parameters	Value
Bit rate	18.78 kbps
Arrival Patterns	CBR/Poisson
Polling Interval Distributions	Deterministic/ Exponential/ Dynamic
Number of Nodes	10
Topology	Linear multi hop
Message Generation Interval	10 to 250 sec
Distance between consecutive nodes	15 m
Duration of Each Cycle T_{cycle}	10 sec
Size of Contention Window	32 Slots
Wake-up Time T_w	300 msec
Sleep Time T_s	9700 msec
Polling Duration T_{poll}	20 msec
Polling Interval T_{PI}	50 msec

Table 2

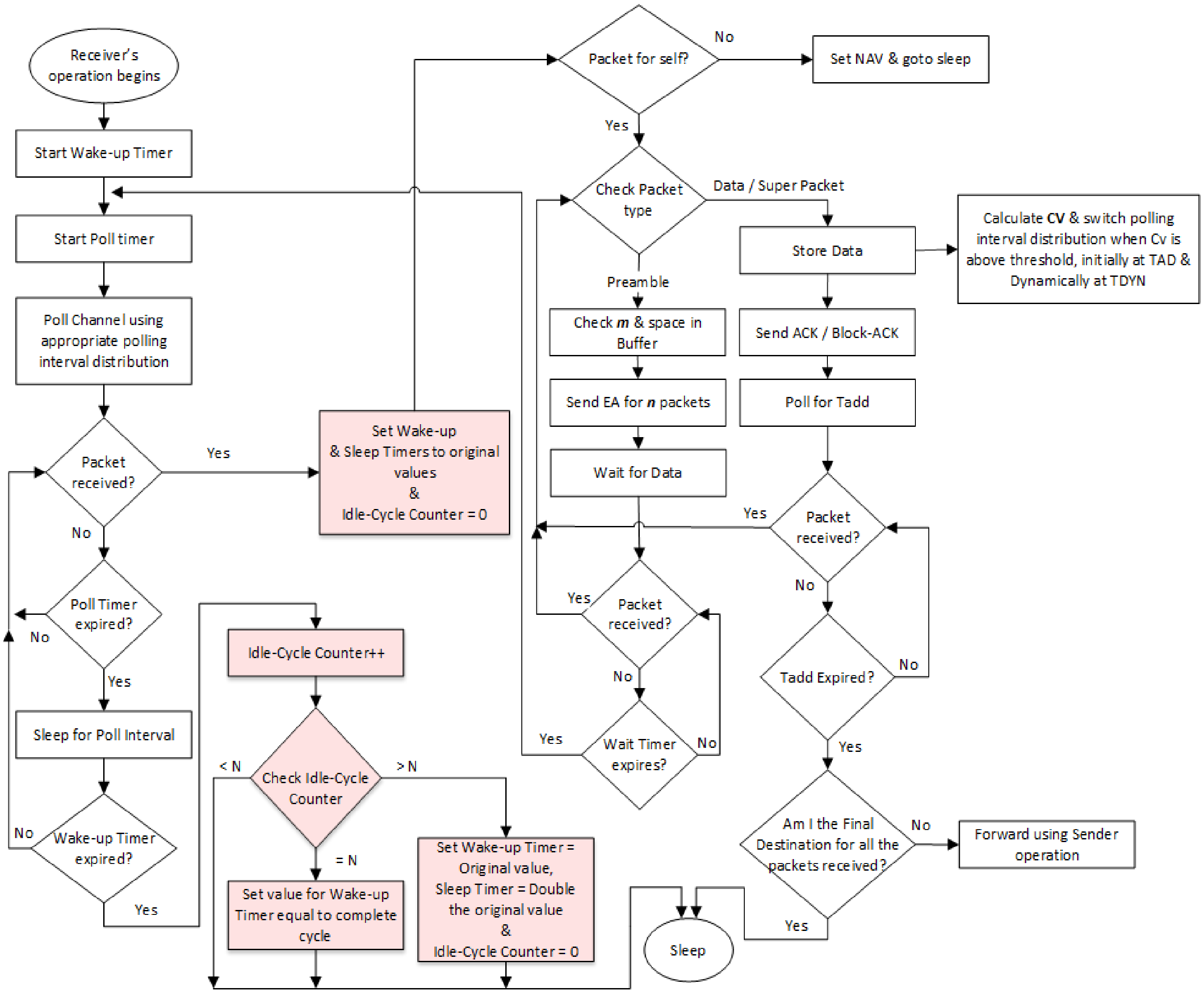
Simulation Settings for Comparing ADP-MAC with T-AAD

Simulation Parameters	Value
Simulation Duration	35 min
Simulation Environment	Multi-sender
Topology	50 x 50 grid
Number of Nodes	50 (49 senders, 1 sink placed at the top left of grid)
Topology	Linear multi hop
ST_{min} (Minimum Sleep Time for T-AAD)	32 msec
ST_{max} (Maximum Sleep Time for T-AAD)	50 msec

The rationale behind differences between expected and detailed implementation results is the fact that the high-level predictions 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 and 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. Moreover, there was no implementation of the preamble transmissions, collisions, CSMA/CA process, and retransmissions; all these details were taken into account in the actual implementation of the ADP-MAC. Therefore, the differences occurred due to the lack of realistic assumptions about channel and network conditions in the preliminary simulations.

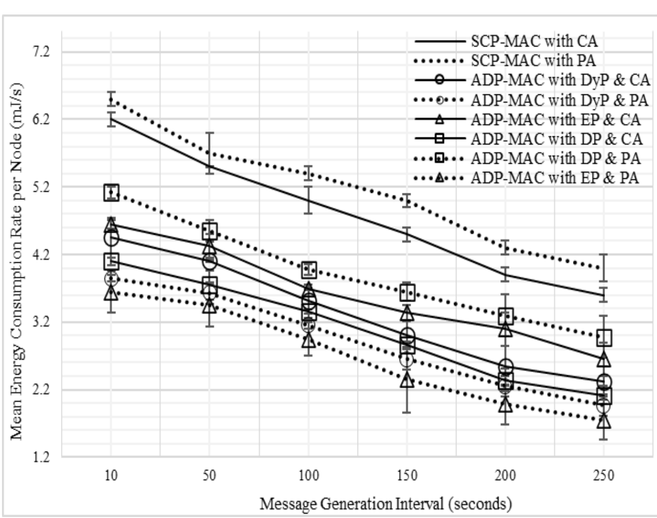

Wake-up
Packet to send?
No
Follow Receiver's Operation
Yes
Carrier Sense
No
Yes
Channel Busy
Yes
Wait for Back-off period
Packet Identified
Yes
Packet for self?
No
Set NAV & goto Sleep
No
Send Preamble for m packets
Send Preamble for remaining packets
No
Check all transmitted packets have been acked
Wait for EA for Tpause
No
Preamble limit crossed?
No
EA received for n packets
Yes
Yes
Sleep for Ts
No
Another packet in Buffer ?
Yes
Drop the Packet
Yes
Send Packet / Super-Packet
Wait for Ack / Block Ack
Yes
EA received for this Packet?
No
Sleep for short interval Tpause
Yes
Retry Limit crossed
No
ACK / Block ACK received
Yes
ACK or Block ACK ?
ACK
No
Block ACK

(a)



(b)

Fig. 4. Operation of ADP-MAC: (a) Sender (b) Receiver



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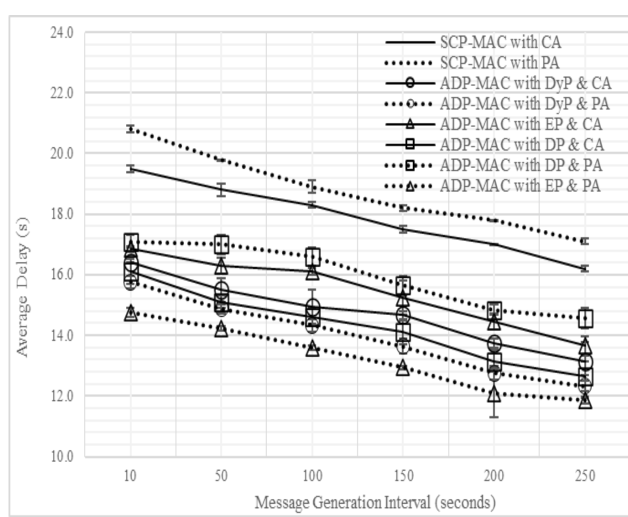

(b)

Fig. 5. Performance evaluation of ADP-MAC for varying traffic load (a) Energy (b) Delay

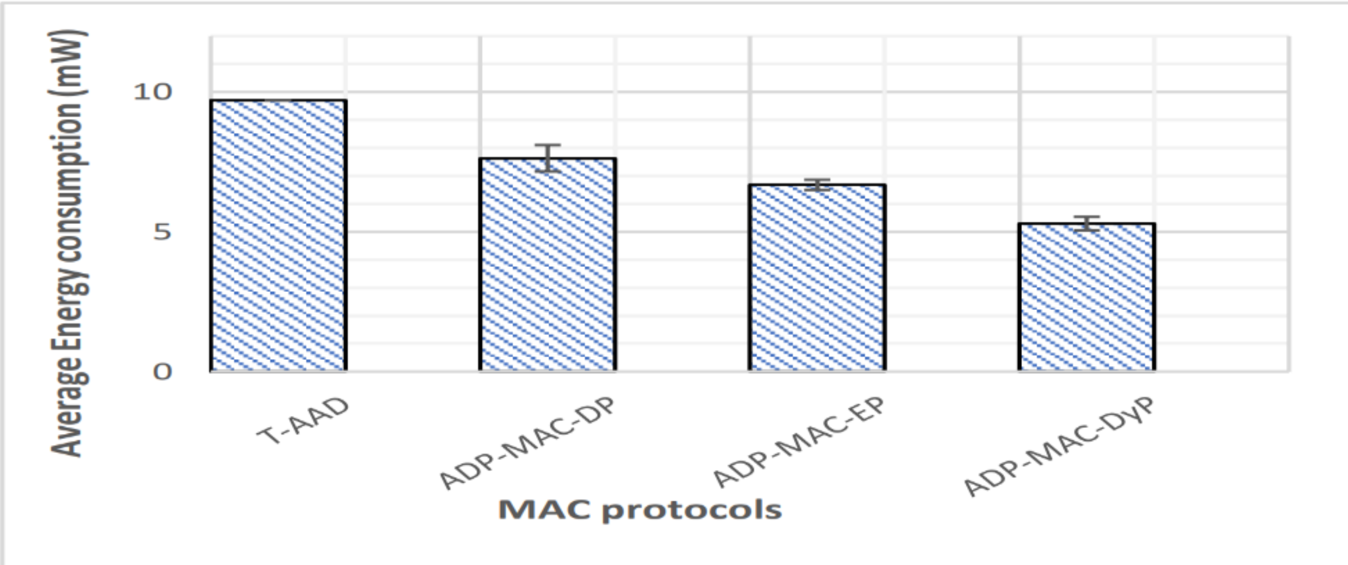

Fig. 6. Energy performance comparison of ADP-MAC with T-AAD.

5. Conclusion

This paper presented a detailed road map for developing a MAC protocol for WSN. The milestones of gap identification, developing proof of concept, protocol design, protocol implementation and analysis and comparative performance evaluation have been described. Each milestone has been described in the light of development experience of ADP-MAC which is a novel asynchronous MAC protocol. We also provided markers of the milestones where the work can be published. The article is expected to aid the researchers in their journey of systematic MAC protocol development.

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