Traffic-Aware Adaptive Wake-Up-Interval for Preamble Sampling MAC Protocols of WSN

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***Abstract*—Medium access control MAC layer plays an important role for energy management in wireless sensor network (WSN). In this paper we present an adaptive wake-up-interval scheme for preamble sampling (MAC) protocols for variable traffic in WSN. The wake-up-interval is updated based on the traffic status register (whose contents depend on the presence of messages for a particular node). The proposed algorithm considers dominant effect of recent traffic with regards to the old traffic and also it relies on the occurrence of consecutive data packets. The results show that the sensor node adapts and converges its wake-up-interval to the best trade-off value for fixed and variable traffic patterns. Two optimization parameters (length of traffic status register and initial wake-up-interval value) are also tuned to achieve fast convergence speed for different traffic rates and variations.**

I. Introduction

In WSN energy efficiency is one of the important design objectives because most of the sensor nodes are powered by limited battery source. In typical WSN platform, the radio transceiver consumes most of the power. Radio activity is controlled by the medium access control (MAC) layer, therefore it is necessary to design a low power and energy efficient MAC protocol. In these regards, low duty-cycle protocols such as preamble sampling MAC protocols are very effective because these protocols reduce the energy waste caused by idle listening, overhearing and overheads [8].

Wireless sensor networks (WSNs) have obtained a great relevancy in civil as well as military applications such as environment sensing, real-time surveillance and habitat monitoring. In most of the WSN applications data transmission rate depends upon the occurrence of the events, the traffic during normal circumstances will be significantly lower in comparison to the case when an event occurs. Also, in typical WSN the flow of data transmission towards the sink node is more dominant with regards to other nodes which are away from the sink.

In the context of traffic aware MAC protocol design, [4] presents a traffic adaptive duty cycle protocol that can extend the duty-cycle as soon as the traffic increases, presented approach enhances the energy efficiency, and end-to-end delivery ratio. Similarly, [5] proposes an event dependent traffic-aware MAC protocol for tree topology which performs better than fixed duty cycle protocols for surveillance applications. With regards to the traffic load distribution among different nodes within a network, [3] presents an optimal stochastic based traffic distribution model which provides efficient load balancing approach. Routing independent and fair energy allocation scheme for multi-hop WSN is presented in [1]. Moreover, for dynamic traffic several distributed routing algorithms were proposed as well for energy efficiency. Adaptive duty cycle MAC protocol presented in [5] is suitable only for tree topology. It contains super-frame structure with *listen schedule frame* which consumes significant energy due to idle listening at receive mode. [4] increases or decreases the duty cycle according to the traffic but it is limited for synchronous protocols. Therefore, for distributed asynchronous sensor network there is a strong need for adaptive MAC protocol to minimize the energy waste due to idle listening.

In this paper we present an adaptive wake-up-interval for MAC protocols that can be widely used for WSN applications. Wake-up-interval is the most important design parameter in preamble sampling MAC protocols, since it regulates the amount of time the node is listening to or transmit to the wireless channel. Therefore the wake-up-interval (WUInt) has a dominating impact on the energy efficiency of the protocols. In the proposed technique, every node adapts its WUInt with regards to the amount of traffic (i.e. data packets) it receives and consequently optimizes the energy consumption for different applications. The adaptation of WUInt optimizes the energy by two ways; first, it reduces the unnecessary transmission of wake-up-beacon (WUB) and second it reduces the idle listening by adjusting the wake-up-time (WUTime) of the transmit node with regards to the receive node. Traffic status register (TSR) is used to estimate the WUInt. Important design parameters are the length of TSR and initial WUInt value. Results show that the WUInt converges to a steady state value after several wake ups and the proposed algorithm also converges very fast whenever the data rate changes due to the various application scenarios. Furthermore the best values (in terms of convergence rate) for the length of TSR and initial wake-up-interval are presented for variable traffic patterns.

The rest of this paper is organized as follows. In Section II, we present various application scenarios and energy efficient category of MAC protocols called preamble sampling. In Section III, we introduce the low power adaptive MAC protocol followed by the results of the proposed protocol in Section IV. The paper ends with the conclusion and future works. A list of acronyms are presented in the appendix to help the readability.

II. Application Dynamics And MAC Protocols

In this section we will present different application perspectives of wireless sensor networks and distributed asynchronous MAC protocols in context of cross layer design of application based MAC protocols.

A. Application Scenarios And Traffic Pattern

For various WSN applications such as environment sensing (temperature, sound, vibration, humidity), real-time surveillance (intrusion detection, tracking) habitat monitoring [2], traffic models are described by on-demand or event-based models. On-demand model has periodic traffic flow, whereas event-based model generates burst of traffic on the occurrence of events. In this regards few application scenarios are sufficient to include majority of WSN applications.

- Environmental monitoring applications normally transmit data at periodic interval during normal circumstances but as soon as there is an event, sensor nodes transmit burst of data with much faster rate. For example, in temperature sensing application sensor nodes wakeup periodically to sense the environment and communicate information with other nodes. In the same application whenever there is an event such as fire or alarm detection the traffic pattern will be completely different.
- In real-time surveillance applications the traffic is very low when there is no event, but as soon as the intruder or object is detected there exist burst traffic. For example, in object detection based multimedia applications the traffic load follows heavy-tail distribution [6] which means that normally very low information exchange for a long period of time but as soon as there is an event information size increases very fast in very short time.

It is necessary that MAC, Routing, Physical layers incorporate various dynamics of application scenarios as explained above in their design phase. In this paper we present an adaptive MAC protocol based on different application scenarios.

B. Preamble Sampling MAC Protocols

Medium Access Control (MAC) is the ability of a node to efficiently share the wireless medium with the other nodes in the network [8]. The main objective of the MAC layer is to keep the energy consumption low by turning off the radio module as often as possible. In the design of energy aware MAC protocols, the main causes of energy consumption are idle listening, overheads, overhearing and collisions. In order to achieve the highest energy efficiency these factors need to be minimized, but there exists a trade-off for the optimal design. For example, the protocol with the aim to reduce idle monitoring and collisions demands extra synchronizations and overheads, whereas, reducing the overheads and synchronizations results in an increase in energy waste due to collisions.

In the context of energy efficient WSN protocols, the preamble sampling method is an attractive option for light WSN traffic [8]. Preamble sampling MAC protocols are based on non-scheduled mechanism without any synchronization among the nodes, which means that each node is completely independent of its own active/sleep strategy. The general mechanism of a preamble sampling protocol is shown in Fig. 1. The initialization of communication between sensors can be initiated by either a transmit or a receive node (depending upon the specific protocol being used) both cases are depicted in Fig. 1. If the communication is initiated by the receiver, the receive node will send the preamble to the transmit node and the transmit node will respond with the data packet, whereas if it is initiated by the transmitter then the preamble will sent by the transmit node followed by the data packet. The receive node wakes up periodically at sampling interval to sense the channel activity and if it does not find any preamble it goes to sleep mode immediately. It is to be noted that, preambles have to be long enough such that the intending receive/transmit node can be able to receive the preamble on the wake up and further to keep the radio on for receiving the subsequent data packet.

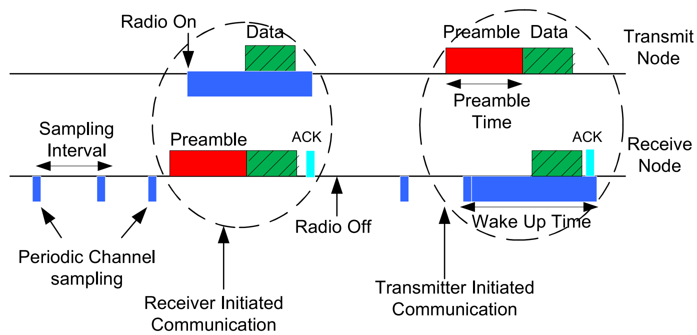

Fig. 1. General mechanism of preamble sampling protocols. Every receive node wakes up with a specific sampling interval called as wake-up-interval $WUInt$, and samples the channel. The communication can either be initiated by receive or transmit node. In transmit initiated communication, after the channel sensing the transmit node sends the preamble. The receive node on the wake up waits for the preamble and as it finds the preamble it remains awake until data is received otherwise it goes to sleep. Whereas, in receiver initiated communication, it is the receive node which sends the preamble to transmit node, the intended transmit node sends the data in reply to preamble. The communication finished with acknowledgment in both the cases.

Preamble sampling category includes energy efficient MAC protocols such as Cycled Receiver i.e. RICER (Receiver Initiated Cycled Receiver) [7], TICER (Transmitter Initiated Cycled Receiver) [7], LPL (Low Power Listening)/B-MAC (Berkeley MAC) [9], X-MAC [10], WiseMAC [11] etc. These protocols reduce the cost of extra overheads (in comparison with scheduled based protocols) and synchronizations by having short preambles. In addition, a protocol like WiseMAC can adjust the duty cycle efficiently based on the wake-up-time of the neighbor nodes, which results in a great reduction of idle monitoring for fixed traffic.

III. Low Power Adaptive MAC Protocol

Wake-up-interval is the most important design parameter in MAC protocols. For periodic sensing or even event driven applications usually it is kept fixed, which results in degrading the performance as well as the energy efficiency. In our previous research work on scenario-based hybrid energy model [12] for preamble sampling category of MAC protocols, it was concluded that adaptive wake-up-interval can help to optimize the energy consumption by reducing idle listening which is the most significant energy waste in distributed asynchronous sensor networks.

In this paper we present adaptive wake-up-interval for variable traffic that can be applied to other low power asynchronous MAC protocols such as B-MAC [9], X-MAC [10], WiseMAC [11], CyclED Receiver [7] to reduce their energy consumption. Wake-up-interval is estimated based on the traffic status register (TSR) shown in Fig. 2. TSR is filled with one as an input (to the first index of the TSR), if a node receives a data packet otherwise it is filled with a zero. Register is divided into two halves in order to consider dominant impact from the most recent traffic (which resides in the 1^{st} half) in comparison to relatively old traffic (which is in 2^{nd} half). TSR can have different patterns depending upon the variations in the traffic and position of the node, further it is used to evaluate the next wake-up-interval and helps to reduce the unnecessary wake-up-beacon or preamble transmissions.

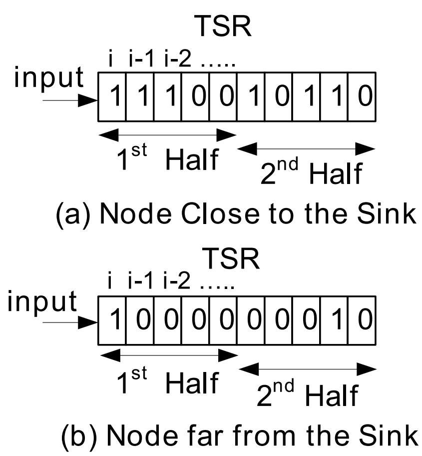

Fig. 2. Input of the traffic status register (TSR) contains one if a node wakes up and receives a data packet otherwise it contains zero. TSR is a shift register with a new input stored at index i. Different patterns depending upon the variations in traffic and position of the nodes are possible in the register. Further it is used to evaluate the next wake-up-interval, for that matter, register is divided into two halves and we give more weight to the first half as it contains the latest traffic with respect to the second half.

As the node wakes up, it computes the next wake-up-interval based on the TSR. Wake-up-interval is updated for the time instant $(i+1)$ based on the value at time instant (i) plus the current update μ at instant (i) as,

$$WUInt(t_{i+1}) = WUInt(t_i) + \mu(t_i) \cdot t_{ref} \tag{1}$$

In order to have unique reference of time among $WUInt$ and μ, t_{ref} is multiplied with μ, and it is defined with reference to the system/simulator clock. Update factor μ is calculated based on first (X_1) and second (X_2) halves computation along with constant weighting factor α as,

$$\mu = \alpha \cdot X_1 + (1-\alpha) \cdot X_2 \tag{2}$$

Whereas X_1 and X_2 are calculated through following equations

$$X_1 = \frac{N_{01}}{L/2} \cdot Nc_{01} - \frac{N_{11}}{L/2} \cdot Nc_{11} \tag{3}$$

$$X_2 = \frac{N_{02}}{L/2} \cdot Nc_{02} - \frac{N_{12}}{L/2} \cdot Nc_{12} \tag{4}$$

N_{01}, N_{11}, Nc_{01} and Nc_{11} are the number of zeros, number of ones, occurrence of consecutive zeros and occurrence of consecutive ones in X_1 respectively, whereas, N_{02}, N_{12}, Nc_{02} and Nc_{12} are the number of zeros, number of ones, occurrence of consecutive zeros and occurrence of consecutive ones in X_2 respectively. Further the tuning parameter such as L is the length of TSR.

In the proposed algorithm the most influential parameter is Nc (occurrence of consecutive zeros or ones). Even though there are multiple ones or zeros in the TSR they will not make an impact on the update value of wake-up-interval until there are consecutive or back-to-back zeros or ones. Multiple consecutive zeros employ that the next wake-up-interval should be increased in comparison to the previous value, whereas multiple consecutive ones imply that the next wake-up-interval should be decreased.

IV. Results

In this section the simulation results of the proposed adaptive wake-up-interval algorithm are presented. The results presented below are initial results therefore they are limited only for two nodes, but the results presented are a proof of concept which will be extended for a larger network in future.

Traffic status register (TSR) contains either one or zero depending upon if a node receives a data packet (as it wakes up) or not. When the algorithm converges to a steady state value it is found that the TSR adapts to a sequence of '10101010...' pattern. This typical sequence seems the best trade-off between the optimal wake-up-interval i.e. (11111111...) and too frequent wake-up i.e. (100010001...). The optimal sequence contains the probability that it may miss a data packet from the hidden node or mobile node whereas the sequence ′10101010...′ can incorporate these effects and consequently adapts the wake-up-interval to another steady state value. The too frequent wake-up sequence wastes the energy consumption by transmitting unnecessary wake-up-beacons.

Fig. 3 shows the adaptation of the receive node wake-up-interval towards a steady state value for a data packet rate of one second. In these results, we consider two nodes for the proof of concept of proposed algorithm. It can be seen in Fig. 3 that there exists a sharp dip after few wake-ups. It is because of the fact that during the evolution phase the wake-up-interval value keeps fluctuating due to the reception of data on every wakeup or in other words, a node receives multiple data (which means multiple consecutive ones in the TSR) that results in sharp reduction of wake-up-interval value.

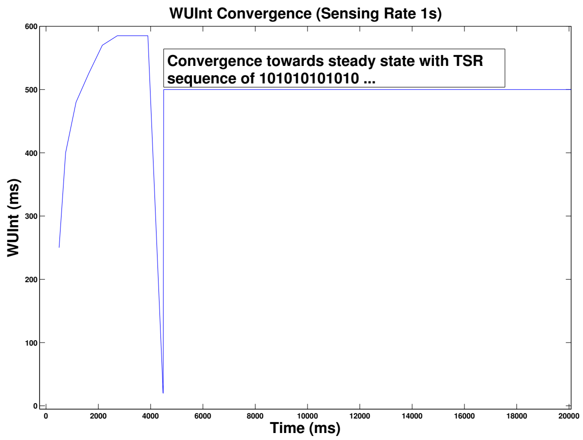

Fig. 3. Receive node adaptation of wake-up-interval for a fixed data rate from transmit node. After several wake-ups the receive node converges towards a steady state value for sensing rate of one second. It is to mention here that the reference clock increment is 1 millisecond (ms), therefore we have all the time values in ms.

Moreover, after few wake-ups the receive node converges to a steady state value. Similarly, sharp peaks are also possible during the evolution phase.

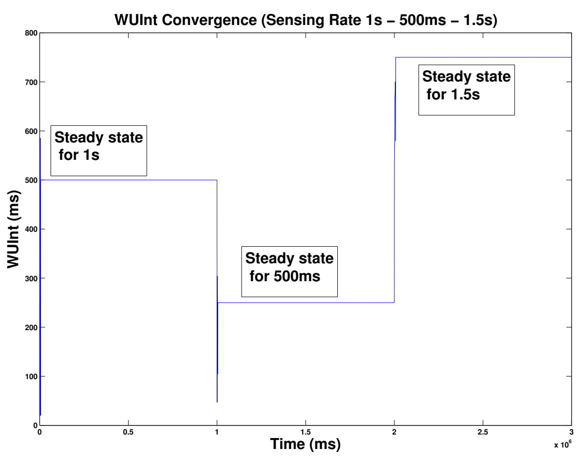

Fig. 4. Convergence of wake-up-interval towards a steady state value for variable sensing rates. Three different rate were considered based on the application dynamics, started from one packet/s, then increased the rate to two packets/s and finally reduced the rate to less than one packet/s

Fig. 4 shows the convergence of wake-up-interval for different traffic rates i.e. $1.0s, 500ms$ and $1.5s$. These traffic rates correspond to various application scenarios for medium to heavy traffic variations. The adaptive technique presented converges to steady state values for all the traffic loads. Further in Tab. I extended results are presented for very low and very high traffic rates. There are two optimization parameters *TSR Length*, *Initial Wake-Up-Interval Value* and a constant parameter α. After several simulations the best value of α is found to be 0.7 (which remains constant during different traffic variations), whereas, the optimization parameters vary according to the traffic rate.

In Tab. I, we present the results of three different patterns of traffic variations from very heavy traffic to normal and then very low traffic and vise-versa. It is found during the simulations that initial wake-up-interval value is important parameter for converging towards a steady state. It can be observed that the initial wake-up-interval values tend to increase if the data rate is increasing and decrease if the data rate is decreasing. Due to this fact, the initial wake-up-interval value is also updated as the traffic pattern changes. In this regard, a value close to half of the sensing rate seems to converge most of the times with fast convergence speed as well. The *TSR Length* is another important parameter of the proposed technique, generally if the length is too short the convergence speed is faster but in the case when there are multiple nodes and with different traffic rate the chances of convergence reduce. Whereas, too long length takes much longer time to converge and in several traffic variations cases it did not converge at all. Tab. I, presents the best possible values in terms of fastest and accurate convergence for variable traffic rates.

TABLE I

OPTIMIZATION OF CONVERGENCE SPEED (IN TERMS OF NUMBER OF WAKE-UPS) TOWARDS A STEADY STATE VALUE OF THE WAKE-UP-INTERVAL FOR VARIABLE TRAFFIC VARIATIONS (PACKET RECEIVED INTERVAL IN SECONDS) FROM LOW TO HIGH AND HIGH TO LOW. INITIAL WUINT VALUE (IN SECONDS) AND LENGTH OF THE TRAFFIC STATUS REGISTER TSR ARE OPTIMIZED ACCORDING TO THE FASTEST CONVERGENCE TOWARDS A STEADY STATE WAKE-UP-INTERVAL VALUE.

Variable Traffic Packet Every(s)	Initial Wake-Up-Interval(s)	TSR Length	Convergence Speed (No. of Wake-Ups)
0.5 - 1.0 - 1.5	0.1 - 0.5 - 0.5	4 - 6 - 8	7 - 14 - 16
0.5 - 1.0 - 2.0	0.1 - 0.5 - 1.0	4 - 6 - 8	7 - 14 - 18
0.5 - 1.0 - 10.0	0.1 - 0.5 - 5.0	4 - 6 - 12	7 - 14 - 15
1.5 - 1.0 - 0.5	0.5 - 0.5 - 0.1	6 - 6 - 4	17 - 4 - 16
2.0 - 1.0 - 0.5	0.5 - 0.5 - 0.1	6 - 6 - 4	15 - 10 - 16
10.0 - 1.0 - 0.5	5.0 - 0.5 - 0.1	10 - 6 - 4	38 - 10 - 16

It is worth mentioning that the above results after convergence to a steady state value (even though for now only between two nodes), consume zero energy due to idle listening but for the real-time physical implementation there will be very little energy waste due to clock drift and hardware latencies. Also the energy consumed by wake-up-beacon transmission is reduced significantly as the numbers of unnecessary wake ups are avoided through proposed technique. The proposed technique can be applied to both transmitter initiated or receiver initiated MAC protocols of preamble sampling category for various applications.

V. CONCLUSION AND FUTURE WORK

Energy consumption due to idle listening and unnecessary wake-up-beacons transmission results in multiple times energy waste with regards to the actual transmission. In this paper we proposed an adaptive wake-up-interval for variable traffic with an aim to reduce the energy waste. Each node has a traffic status register (TSR) which contains the traffic load pattern according to data received or not at every wakeup.

We presented an algorithm that evaluates the update of wake-up-interval based on the previous value plus an update that is computed through TSR. Initial results shows that the proposed algorithm of adaptive wake-up-interval converges to variable traffic rates and consequently reduces the energy consumption. Optimization parameters *TSR Length*, *Initial Wake-Up-Interval Value* are adjusted in order to obtain fast convergence and their values for various variations of traffic rates are presented. In future, we would continue to extend these results for multiple transmit nodes and for a larger network such that we can evaluate the network level energy gain over classical non-adaptive MAC protocols.

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APPENDIX

List of Acronyms

$WUInt$: wake-up-interval
WUB : wake-up-beacon
ACK : acknowledgment
$WUTime$: wake-up-time
TSR : traffic status register
X_1 : first half of the status register
X_2 : second half of the status register
N_{01} : number of zeros in first half
N_{11} : number of ones in first half
N_{02} : number of zeros in second half
N_{12} : number of ones in second half
Nc_{01} : occurrence of consecutive zeros in first half
Nc_{11} : occurrence of consecutive ones in first half
Nc_{02} : occurrence of consecutive zeros in second half
Nc_{12} : occurrence of consecutive ones in second half
L : Length of the traffic status register
α : Constant weighting factor
μ : update factor