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PRIB-MAC: a preamble-based receiver initiated MAC protocol for broadcast in wireless sensor networks

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Abstract. Synchronizing data communication between nodes with energy efficiency by adapting different duty cycling mechanisms is the most important task of Medium Access Control (MAC) protocol in wireless sensor networks (WSNs). Most of the low-duty-cycle MAC protocols address the issue of unicast efficiently, ignoring the broadcast performance, which presents significant challenges due to the duty cycling. In this paper, we propose an asynchronous low-duty-cycle MAC protocol for broadcasts in WSN that incorporates the advantages of existing sender-initiated and receiver-initiated MAC protocols. The Preamble-Based Receiver-Initiated Broadcast MAC (PRIB-MAC) protocol is built on RI-MAC unicast MAC protocol by adding a preamble to support broadcasting. It is found that the duration of the preamble depends on the time difference in the wake-up schedule of the nodes and with an optimized wake-up schedule, the preamble duration of just 2% of the slot duration can give 100% node coverage in very less time compared with ADB: an efficient multi-hop broadcast protocol based on asynchronous duty cycling in WSNs.

Keywords. WSN; MAC; asynchronous; broadcast; low duty cycling; receiver initiated.

1. Introduction

Wireless sensor networks (WSNs) have tiny, low-power, low-cost and multi-functional nodes with the capability of sensing the environment, collecting the data, processing the data and reporting the data through wireless communication in self-organized manner [1, 2]. WSN can be used in various fields like event-reporting, tracking, remote monitoring and video surveillance applications like military [3], medical [4], industry [5], agriculture [6], home [7], sports [8], security [9] and others [1, 2, 10]. WSN is also used to connect electronic and non-electronic devices through Internet of Things (IoT) and in ubiquitous computing to connect the computing devices anywhere and anytime [10–14]. To perform the operations of the afore-mentioned applications, a node in WSN may operate many years without human intervention with limited resources, memory and energy. As nodes in WSN are battery powered, if the energy of any single node among the network gets drained out, it degrades the performance of the entire network. Therefore, to improve the performance and prolong the lifetime of the network, energy efficiency [1, 2] is an important factor in WSNs.

Medium Access Control (MAC) protocol is a key factor to improve the battery life time, throughput, latency and QoS through better utilization of the medium [1, 2] in WSN. The MAC protocols designed for conventional networks are less energy efficient due to ideal listening, collision, overhearing and protocol overhead. The MAC protocols for WSN adopt low duty cycling to achieve energy efficiency and can be broadly classified into synchronous and asynchronous duty cycle protocols.

The synchronous duty cycle protocols require adjusting the schedules with neighbours. It reduces the latency time but requires a synching mechanism at each node, which increases energy consumption. The nodes in asynchronous duty cycle protocols wake up based on their own schedule and several mechanisms are proposed for coordination of source and receivers to complete the transmission of data [15–18]. Sender-initiated MAC protocols follow a mechanism where the sender node sends a long preamble that is sufficient to be received by the receiving nodes before sending the data. Though it is efficient in establishing the coordination, it causes interference with the non-participating nodes and thereby reduces the channel utilization. Another mechanism is the receiver-initiated MAC protocols where the sender node waits for a signal from the receiving node before sending the data and this replaces the

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long preamble with beacons from the receiver node, which significantly improves network utilization and throughput.

Most of these existing energy-aware MAC protocols with asynchronous duty cycling [15–18] address the issue of unicast, i.e. the delivery of data from source to a destination node, efficiently. However, with the advent of IoT [10–14], the scope of the WSN network has increased from local network on the internet and with the advent of WSN applications in IoT environment, wide range of applications with broadcasting requirements are evolving, such as a central system sending firmware updates to all nodes With varied use case for WSN applications, the broadcast performance at the MAC layer should also be thoroughly researched [19–22] and reviewed and this serves as a motivation for our work. In this paper we design the PRIB-MAC protocol that supports broadcast traffic efficiently. It is designed based on RI-MAC [13] protocol and its simulation results are compared to those of ADB [20].

The rest of the paper is organized as follows. Section 2 presents the related work in the area of broadcast support in asynchronous low-duty-cycle sender-initiated MAC protocols like WiseMAC, X-MAC, B-MAC and asynchronous low-duty-cycle receiver-initiated MAC protocols like RI-MAC/ADB, efficient opportunistic broadcast over low-duty-cycle MAC protocols and YA-MAC. Section 3 presents the design and implementation of PRIB-MAC protocol. In section 4, we present the evaluation of PRIB-MAC protocol with simulation results and comparison to ADB, the state-of-the-art RI-MAC-based broadcasting scheme for Asynchronous Duty Cycle Networks. Section 5 concludes the paper.

2. Related work

Some of the recent works in the area of integrating broadcasting requirements with the asynchronous low-duty-cycle MAC protocols present schemes that are implemented on either sender-initiated MAC protocols [19, 23] or receiver-initiated MAC protocols [20, 24].

The preamble-based sender-initiated MAC protocols like WiseMAC [17], B-MAC [18] and X-MAC [19] keep the receivers awake long enough so that the sender can send broadcast data at once. The data is sent after the preamble duration and all the neighbours receive it. However, these very long preambles may cause contention when multi-hop broadcast is considered. Broadcasting based on variable preamble length [15] proposes small-length preambles over B-MAC protocol to perform broadcasting. However, only a subset of nodes listens to the packet and it does not address hidden terminal problem.

The beacon-based receiver-initiated MAC protocols like RI-MAC [13] and ADB [20] avoid long preambles as they occupy the channel for a long time, causing contention and congestion. RI-MAC [13] avoids the hidden terminal issues of the sender-initiated protocols but its broadcasting support is limited as the wake-up duration of the nodes is very short. One of the broadcasting methods proposed is repeated unicasting, which is inefficient as it results in poor utilization of the channel. This is further improved using repeat request (ARQ)-based broadcast method in ADB [20], which proposes transmitting unicast traffic repeatedly to every neighbour receiver node. This results in the sender node duplicating transmissions. It also uses long footers as part of the beacons to track the neighbours that have already received the broadcast message. Also the duplication linearly increases corresponding to the count of the neighbouring receiver nodes, causing low channel utilization, resulting in performance degradation and poor energy utilization at the receiver nodes. The operation of RI-MAC/ADB broadcast scheme is shown in figure 1.

Efficient Opportunistic Broadcasting over Duty-Cycled WSNs [24] proposes a deferring time to reduce the number of transmissions in the network and broadcast latency. To accommodate more receivers, the sender differs the broadcast by $\delta = 1$ time slots or $\delta = q$ time slots where q is the quorum size calculated by quorum-based schedule. Hence, it needs book-keeping and synchronization over the asynchronous wake-up schedules, and this adds additional control overhead at each node.

YA-MAC [25] proposes an Emergent Broadcast Slot that is loosely time synchronized for multi-hop broadcasting. According to this solution, broadcasting is performed only in this time-synchronized slot. However, it requires the schedule knowledge of neighbours, which defeats the purpose of asynchronous duty cycling. Correlated flooding [26] makes use of link correlation [27] and dynamic forwarder selection to perform efficient flooding. However, this protocol requires learning of neighbour's schedule. Broadcasting based on variable preamble length [23] is very close to our work and uses a small-length preamble over B-MAC protocol to perform broadcasting. However, it does not address hidden terminals. Our work is different

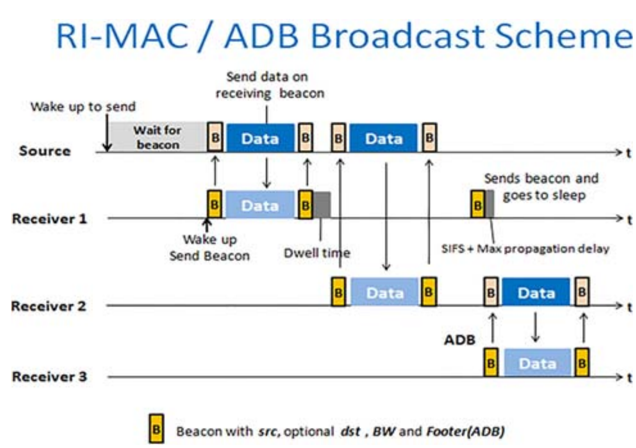

Figure 1. Operation of RI-MAC/ADB broadcast scheme.

from [23] in the sense that it uses RI-MAC as the base to address hidden terminals effectively.

Most of these existing broadcasting mechanisms have their own inherent advantages and disadvantages. This serves as the motivation of our work in PRIB-MAC, to combine the advantages of these mechanisms for broadcasts and at the same time eliminating their disadvantages or keeping it to a minimum [13, 19–27].

3. Proposed PRIB-MAC protocol

In this paper, we propose a new broadcasting protocol called Preamble-based Receiver-Initiated Broadcasting MAC (PRIB-MAC) protocol. PRIB-MAC is built on top of RI-MAC. This protocol differs from RI-MAC mainly in the way it handles broadcast data. The remaining features are designed in par with RI-MAC. The PRIB-MAC protocol is designed for handling broadcast traffic efficiently instead of relying on multiple unicast in RI-MAC. PRIB-MAC differs from existing MAC protocols by combining the preamble-based sender-initiated approach and beacons of the receiver-initiated approach.

The design goals of PRIB-MAC protocol are mentioned as follows:

- reduce the number of transmissions,
- reduce the broadcast latency,
- reduce the energy consumption of sender,
- reduce the number of collisions by addressing the hidden terminals effectively and
- address both broadcast and unicast efficiently by adding overhead to unicast flow.

3.1 *Protocol design*

PRIB-MAC is a receiver-initiated multi-hop broadcasting protocol that uses a small preamble to cover a set of nodes in the neighbourhood to broadcast the data. The operation of the PRIB-MAC protocol is depicted in figure 2.

The source with data to be broadcasted wakes up and waits for a beacon from one of its neighbours. On receiving the beacon, the sender delays broadcasting of data by sending a short preamble. During this preamble interval, a certain fraction of the receiver nodes wake up. The sender broadcasts the data to the receivers that wake up during the preamble time frame. The preamble is necessary to keep the receiver nodes awake while the sender delays the transmission of the data. The nodes that receive the data further broadcast the data to the rest of the nodes in their neighbourhood. In order to ensure reliability and avoid acknowledgement explosion issue, PRIB-MAC uses a NACK (Negative Acknowledgement) beacon. If the receiver does not receive the data after receiving the preamble, it sends the NACK beacon to the sender requesting retransmission.

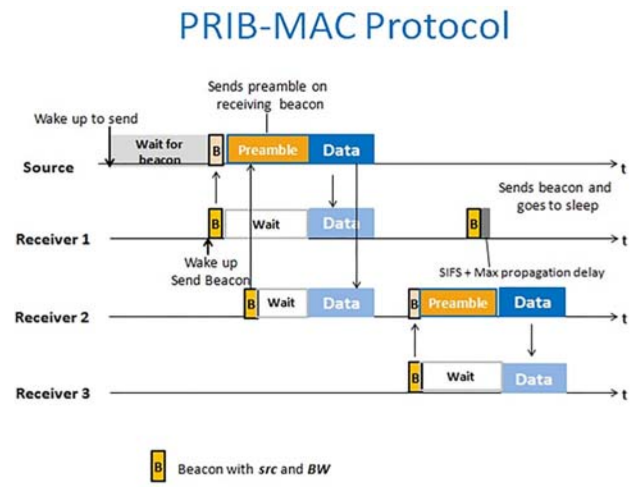

Figure 2. Operation of PRIB-MAC protocol.

The use of short preambles reduces the number of transmissions as compared with RI-MAC, as during this preamble interval, a certain fraction of the receiver nodes wake up, thereby reducing the need for repeated unicast. It is also energy efficient on the sender side as compared with B-MAC because it delays the sending of preamble till it receives the beacon. The preamble duration is much smaller than the slot duration, thus reducing the contention caused in the network. It also handles collisions by scheduling back-off timers with the help of beacon, thereby addressing hidden terminal effectively. Since PRIB-MAC is built on RI-MAC, unicast traffic is addressed efficiently in the same way as the RI-MAC.

3.2 *Implementation*

To implement the PRIB-MAC protocol, first we implemented RI-MAC protocol. The RI-MAC protocol is implemented as a finite state machine model as shown in figure 3.

The nodes in figure 3 represent the states and the arrows represent the state transition. The event that causes the state transition is mentioned on the arrows. If no events are mentioned on state transition, the transition happens soon after completing the current state operations. The model incorporates both RX and TX states and the flow is decided based on whether the node is acting as a source or receiver.

The node is in Init state when it is booted up, and makes a transition to sleep state after initializing the MAC layer parameters for that node. A wake-up timer is set to wake up at every *slot duration* interval. When the node wakes up, it checks for the data from the upper layer. If the data is present, this node acts as the source and waits for beacon. If

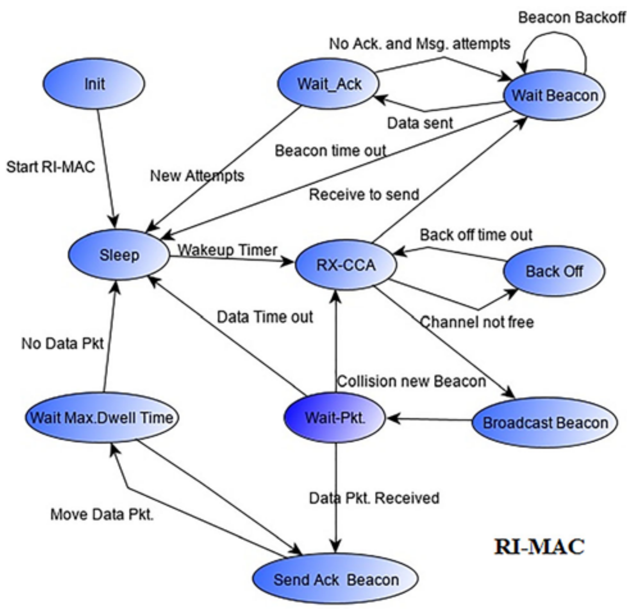

Figure 3. RI-MAC finite state machine model.

not, it transmits beacon and waits for data. If there is no data received after a particular interval of time (SIFS + Max. Propagation delay), the node goes back to sleep. If the data is received, then it sends an acknowledgement (ACK) beacon, waits for dwell time to receive more data from the same source and then goes to sleep. The PRIB-MAC protocol is implemented on top of RI-MAC with the modified finite state machine as shown in figure 4. The states that are modified are highlighted in different colours. Primarily, new states are added to send and receive preambles and a NACK is sent instead of ACK.

In addition to this proposed change of events with the introduction of preambles, we propose two optimizations that would reduce the preamble duration and number of preambles sent by a significant amount.

Optimization-1: The preambles are nothing but the special packets sent back-to-back to keep the nodes awake. When the receiver receives a preamble, it waits for the data till data timeout event occurs. On receiving every preamble, this timer is refreshed. Hence, instead of sending several preambles back-to-back, the source can send preambles after a particular interval of time that is less than the data timeout interval for receivers that are already awake. The nodes that wake up in the inter-preamble duration send beacon and wait for the same data timeout interval, thus receiving the next beacon. The following formula explains the calculation of interval between preambles:

$$t_{\text{int}} = t_{\text{timeout}} - t_{\text{chk}} \tag{1}$$

where t_{int}, t_{timeout} and t_{chk} are interval between preambles, data timeout interval of receivers and check interval of the network, respectively.

Optimization-2: There is a close relationship between the wake-up schedules of the nodes and the preamble duration. If the wake-up schedules of the nodes in the neighbourhood are very close on the timeline, then the preamble duration required is very less. In order to do this, we need not synchronize the schedules of the neighbouring nodes. This is different from the RI-MAC design, which requires the wake-up schedule to be distributed between $0.5L$ and $1.5L$ to avoid beacon congestion, where L is the slot duration. Hence, the solution is to reduce this interval by 10 times/100 times.

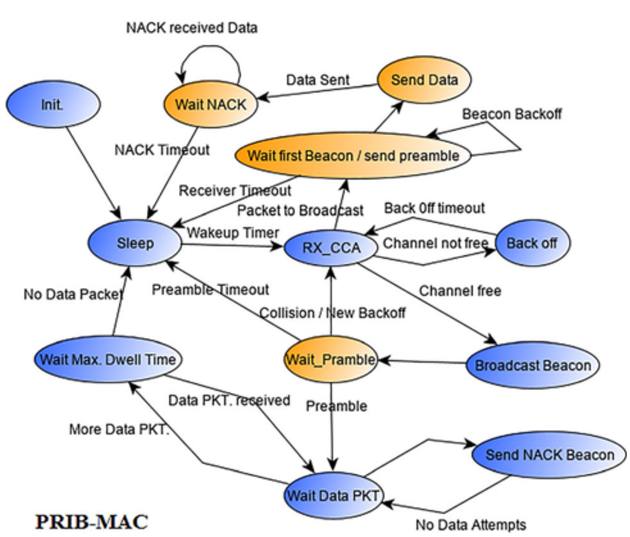

Figure 4. PRIB-MAC finite state machine model.

Algorithm-1. PRIB-MAC protocol

```
check channel
if channel is free and data to send then
   switch to Tx mode
   wait for beacon
     if s receive beacon from r(n) then
       do
         s send a preamble to r(n)
         wait for t_int
       until t_timeout
     end if
   s broadcast the data packet
else
switch to Rx mode
   if preamble received from n then
     wait for data from n after the preamble.
   end if
end If
go to sleep mode
```

4. Protocol evaluation

We evaluated the protocol for various preamble durations to arrive at an optimal preamble length. We have compared the broadcast performance against ADB, which is the state-of-the-art broadcasting scheme for Asynchronous Duty Cycle Networks. Another reason for us to choose ADB for comparison is that it is a broadcasting scheme built on top of RI-MAC.

4.1 *Simulation methodology*

We evaluated PRIB-MAC protocol using MiXiM (Mixed Simulator), which works on OMNeT++ simulation engine [28]. We added PRIB-MAC to the MAC layer of the MiXiM as described in the algorithm in the implementation section. The simulation parameters used for the simulations are tabulated in table 1. We have assumed symmetric links and zero propagation delay for the purpose of simulations. The simulation results of the PRIB-MAC protocol are compared to those of ADB, another RI-MAC-based broadcasting scheme for Asynchronous Duty Cycle Networks.

4.2 *Simulation results*

4.2a *Network coverage time and percentage*: The network coverage percentage for PRIB-MAC with and without the optimizations explained in section 3.2 is shown in figure 5 for different preamble durations.

With a shorter preamble (0.002 s), fewer nodes woke up during the preamble duration and only those nodes received broadcast data to flood down; hence, the coverage was only 71%. However, when the preamble duration is kept longer (0.02 s), more nodes wake up in the preamble duration, improving the coverage to 100%.

The line chart in figure 6 shows the coverage time for different preamble durations. It increases linearly with the preamble duration and it is the same for both optimized and non-optimized, with the optimized PRIB-MAC giving a better network coverage as shown in figure 5.

Table 1. Simulation parameters.

Parameter	Value
Simulation area	300 m
No. of nodes	6–21
Queue length	2
Header length	24 bits
Bitrate	15360 bps
Check interval	0.01 s
Slot duration	1 s
Default dwell time	0.3 s
Analogue model	Simple path loss model
SNR threshold	0.12589254117942
Busy threshold	3.98107170553E–9

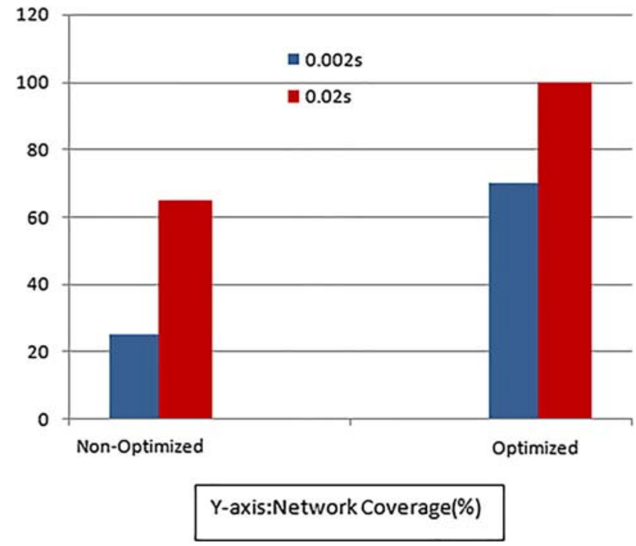

Figure 5. Network coverage percentage (%) for different preamble durations in 21-node network.

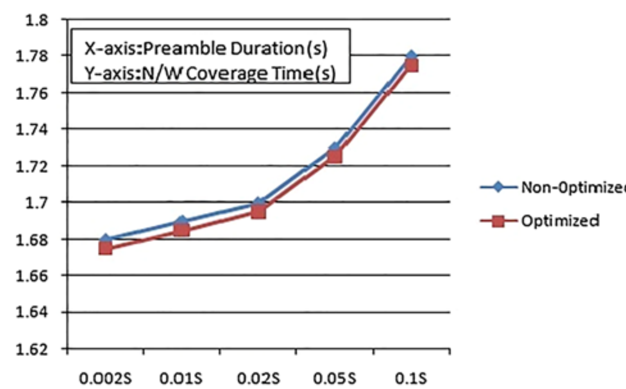

Figure 6. Network coverage time for different preamble durations.

With this optimal preamble duration for PRIB-MAC, figure 7 shows the comparison of the network coverage time against ADB.

The line chart shows linear increase in coverage time as the number of nodes in the network increases. As depicted, PRIB-MAC shows a significant improvement in terms of coverage time as ADB requires repeated transmissions to achieve wider coverage.

4.2b *Control overhead*: Analysis on the control overhead in PRIB-MAC and ADB is shown in figure 8 using a bar chart.

The bar chart has number of nodes in *X*-axis and the percentage of control overhead in *Y*-axis. Compared with PRIB-MAC, ADB has significantly more percentage of control overhead and it increases as the number of nodes in

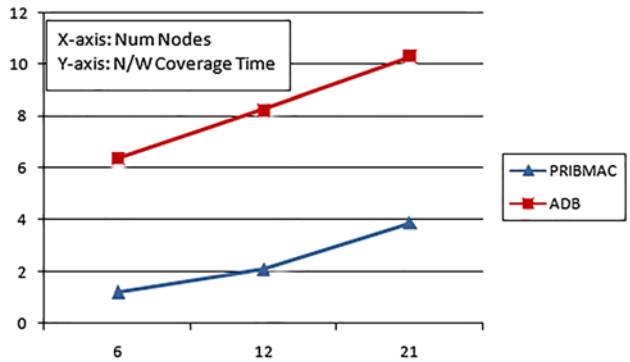

Figure 7. Network coverage time of PRIB-MAC and ADB.

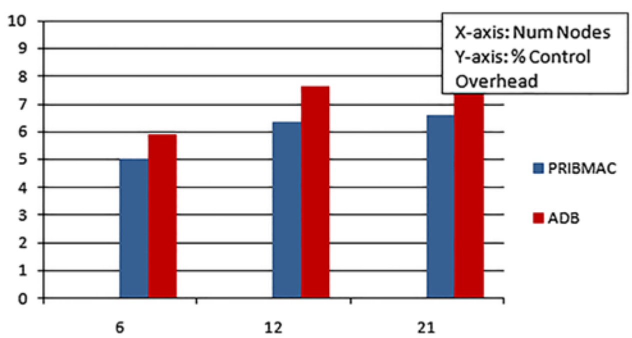

Figure 8. Control overhead of PRIB-MAC and ADB.

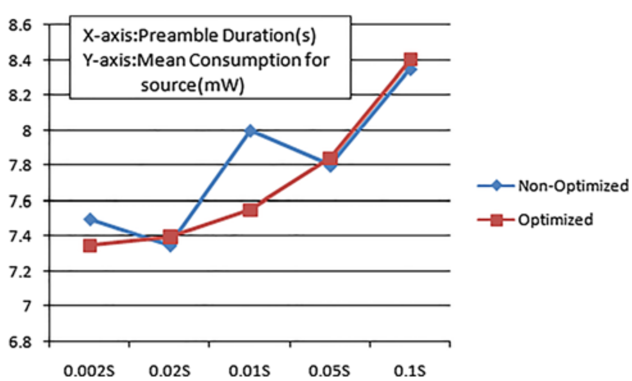

Figure 9. Mean energy consumption for different preamble durations.

the network increases. This is because in ADB, the sender performs repeated unicast with the use of long footers as part of the beacons to track the neighbours.

4.2c *Energy efficiency*: Mean energy consumption at the source for various preamble durations in optimized and non-optimized PRIB-MAC is shown in figure 9.

As the line chart conveys, the energy consumption is more linear for optimized PRIB-MAC. It is obvious and evident that smaller the preamble duration, lesser the

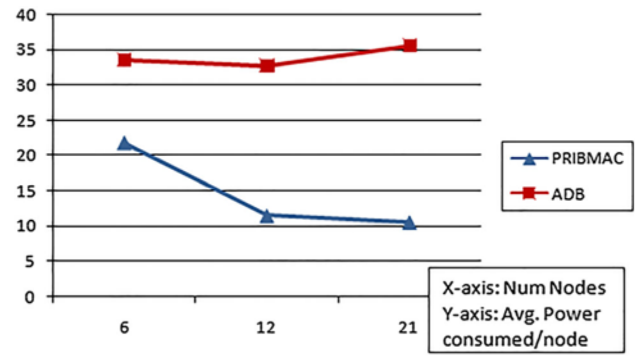

Figure 10. Average energy consumption of nodes for different network sizes in PRIB-MAC and ADB.

energy consumption. However, we observed that the preamble duration of 0.02 s gives complete node coverage for larger network and energy consumption for this duration is lesser too.

When the wake-up times of the nodes were not that close enough (i.e, each node woke up in a wider interval), some of the forwarding nodes (those that received data from the source and were designated to forward data down the network) woke up at a time (while waiting to send preambles) when other nodes had already woken up, received beacons and started sending preambles. Hence, these forwarding nodes did not have to send preambles to their next level nodes because they had already received data from other nodes. This saves power and reduces communication traffic for non-optimized nodes. However, the adverse effect is that, since some nodes do not send preambles, some of their neighbours will not be covered and hence the reachability becomes poor. In conclusion, the optimized PRIB-MAC with preamble duration of 0.02 s gives the best result. However, if the network size is smaller, preamble duration can be comfortably reduced.

Figure 10 shows the comparison of average energy consumption per node for PRIB-MAC against ADB for different network sizes.

As the line chart, with the number of nodes in *X*-axis and the average power consumption per node in the *Y*-axis, conveys, the nodes in ADB have higher average energy consumption compared with PRIB-MAC as the sender node is required to perform repeated unicast. As a result of this repeated unicast approach, lots of beacons are sent to notify the sender of the receiver and the sender wakes up more time for the receiver to send beacon. Duplicate packets are sent in some cases. We also noticed that for ADB the average energy consumed per node increases as the number of nodes in the network increases, whereas in case of PRIB-MAC the average consumption decreases as the number of nodes in the network increases.

4.2d *Number of transmissions*: The number of transmissions for PRIB-MAC with and without optimizations is shown in figure 11.

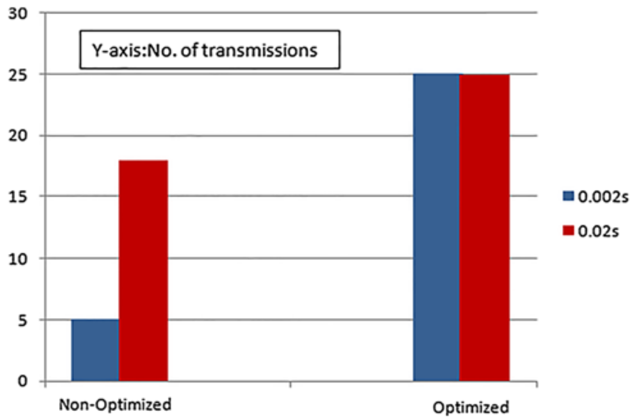

Figure 11. Number of transmissions for 21-node network.

The number of transmissions for optimized PRIB-MAC is more than that for the non-optimized as the optimized has better network coverage percentage as shown in figure 5. The 21-node network has a total of 25 transmissions and the preamble duration has no effect on the number of transmissions. This can be reduced if link correlation is analysed and dynamic forwarder is selected.

5. Conclusion

We have proposed a robust MAC protocol for broadcasting applications in WSNs that leverages the advantages of both sender- and receiver-initiated MAC protocols. Our evaluations of this protocol reveal the relationship between the wake-up schedule of the nodes and the preamble duration. We have successfully established the preamble duration for efficient broadcasting using the proposed PRIB-MAC protocol. With an optimized wake-up schedule, the preamble duration of just 2% of the slot duration can give 100% node coverage in very less time. Our evaluation of this preamble-based approach against the multiple unicast approach proposed in ADB shows significant improvement in network coverage time and average energy consumption of the nodes. We also establish that the preamble duration has no effect on the number of transmissions and this can be reduced if link correlation is analysed and dynamic forwarder is selected, which leaves some future scope for further research.

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