Rationality of Critical Parameters Determination in AS-MAC Protocol for Multi-hop Networks

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Abstract

The wireless medium access being broadcast in nature and hence being scarce sharing resource highly requires optimized medium access control (MAC) protocols. There has been an increasing interest in achieving optimized MAC protocols for WSNs in recent years, especially for the performance metrics of energy-efficiency, latency reduction and throughput. However, it is nontrivial to achieve good performance in different facets of metrics at the same time. AS-MAC protocol achieved a balanced good performance in the abovementioned metrics. Key parameters selection for AS-MAC plays critical role for the optimized performance.

In this paper, we present the rationality of the critical parameters selection for the AS-MAC protocol from both theoretic deduction and experimental results. The selected parameter is the ratio of AS-Period (T_{AS}) over Sleep-Period (T_{Sleep}) for a given total operation cycle (T_{Cycle}) and data package size. The theoretic deduction and experimental results show that rationale determination of the critical parameters play significant role in achieving optimized performance of the protocol for multi-hop networks.

Keyword: Wireless sensor networks; Medium access control; Energy efficiency; Latency; Packet delivery ratio.

I. Introduction

The wireless medium access is broadcast in nature, and hence accessing to the wireless medium becomes scarce sharing virtual resource. This requires highly optimized medium access control (MAC) protocols for wireless sensor networks (WSNs). From wireless sensor networks applications point of view, it is generally true that it is either too difficult or impractical to charge or replace the exhausted batteries, or it is cost-prohibitive to lay power lines for the sensor nodes. All these stringent requirements demand the technologies that can prolong battery lifetime as much as possible and achieve optimized performance at the same time. It is the most challenging issues to solve energy-efficiency issue, at the same time without sacrificing other aspects of performance metrics, such as latency and packet delivery ratio (PDR), in the design of WSNs. Several studies [1] [2] [3] [4] show that idle listening is one of the largest sources of energy consumption at wireless nodes. A number of works have been proposed to reduce the idle listening [4] [5] [6] [7] [8] [9] [14] [15] [16] [17] [18] [19] **Error! Reference source not found.**. Different protocols adopt different approach to provide solution.

AS-MAC scheme **Error! Reference source not found.** that we proposed early introduces an Adaptive Scheduling mechanism to make protocol adaptive to the varying traffic loads so that it can achieve much less energy consumption, much lower end-to-end delay and high throughput in varying traffic loads. AS-MAC scheme adopts three-phase operation cycle, i.e.: Synchronization period with duration T_{SYNC}, Adaptive Scheduling (AS) period with duration T_{AS}, and Sleep period with duration T_{SLEEP}, as its complete cycle. AS-MAC employs timeout-based Resilient Active Time (RAT) mechanism for the Adaptive Scheduling period (AS-period) to achieve adaptability. Hence the ratio of T_{AS}/T_{SLEEP} and timeout value determine the performance of AS-MAC protocol to certain extend. In this paper, we present how to determine a rationale ratio of T_{AS}/T_{SLEEP} so that the designed algorithm can achieve optimized performance in the varying traffic loads. The contributions of this paper are as follows:

- Determination of the rationale ratio of T_{AS}/T_{SLEEP}.
- Theoretic deduction of the rationality of the selected ratio of T_{AS}/T_{SLEEP}.
- Experimental evidence of the rationality of the selected ratio of T_{AS}/T_{SLEEP}.

II. Related Works

T-MAC [7] is one typical example of the efforts to reduce sleep latency, which uses timeout to dynamically determine the length of active period under variable load. That is, the active period ends when no activation event has occurred for a period of time, *TA*. Consequently, *TA* determines the maximum amount of idle listening in the active period. While T-MAC outperforms S-MAC, the performance improvement in term of energy saving is minor, only by 5%, which is achieved with cost of a decreased maximum throughput due to its early sleep problem.

S-MAC with Adaptive Listening (S-MAC-AL) [6] has introduced a new Adaptive Listening scheme into S-MAC to reduce sleep latency. With adaptive listening, a node that overhears its neighbour's transmissions wakes up for a short period of time at the end of the transmission. Hence, if the node is the next-hop node, its neighbour can immediately pass data to it instead of waiting for its scheduled listen period, by which sleep latency will be reduced. S-MAC-AL can reduce end-to-end delay by over 50% compared to S-MAC. And more delay reduction can be achieved with the increase of sensing range. Unfortunately, this achievement comes with much more energy consumption and lower packet delivery ratio with increasing of sensing range [9] because many neighbouring nodes may overhear the RTS or CTS and wakeup, whereas only one of them is the next-hop node. By S-MAC-AL, a packet can be delivered up to two hops, e.g. from A to B to C, in each operational cycle. But it, generally, cannot go beyond two hops within the cycle since the next hop after C is unlikely to be awake due to the limited sensing range.

Demand Wakeup MAC (DW-MAC) [9] has introduced a new low-overhead scheduling algorithm to address the high end-to-end latency problem in multi-hop forwarding and the high energy-consumption problem suffered by S-MAC, T-MAC and S-MAC-AL. DW-MAC uses one-to-one mapping function to prevent collisions in data transmission. By shortening Data period, DW-MAC can achieve shorter end-to-end latency. However, in the DW-MAC, the durations of Data period and Sleep period are fixed. When traffic load increases, Data period might not be long enough for the node that has a burst traffic load to exchange required number of SCH frames. It makes the node have to wait for another cycle, which will increase the end-to-end delay significantly because each cycle is quite long. On the other hand, the fixed Data period can lead to idle listening when the traffic load is light. Since the DW-MAC scheme cannot adapt to the dynamic change of traffic load, idle listening and latency cannot be reduced much under variable traffic load.

With aim to improve the drawbacks in the DW-MAC scheme, our early proposed AS-MAC scheme **Error! Reference source not found.** introduces an Adaptive Scheduling to make protocol adaptive to the varying traffic load so that it can achieve much less energy consumption and much lower end-to-end delay. AS-MAC employs timeout-based Resilient Active Time (RAT) mechanism, dual-role SCH frame with tracked retry number, enhanced proportional mapping and adjustable timeout mechanism; and innovatively combines timeout-based RAT and enhanced proportional mapping in the protocol design, so that it can effectively and efficiently handle both unicast and broadcast traffic.

III. The Operation and Key Features of AS-MAC

The fundamental operation and key features of AS-MAC are re-emphasized to lay the basis of discussion further. AS-MAC is a synchronized duty cycle protocol with each complete cycle divided into three periods:

- Synchronization period with duration T_{SYNC}: During this period, all sensor nodes are synchronized by any synchronization protocol such as the one in [11].

- Adaptive Scheduling (AS) period with duration T_{AS}: Sensor nodes with pending data contend for channel access using a scheduling frame (SCH) which serves as the function as either or both of RTS/CTS in the CSMA/CA in IEEE802.11.
- Sleep period with duration T_{SLEEP}: Most of sensor nodes sleep in this period, and only those having scheduled data transmission wake up to send or receive data and ACK message.

The following design points and features of the AS-MAC play decisive roles leading to the improved performance of the protocol:

A. Adaptive Scheduling Period

AS-MAC designed a timeout-based Resilient Active Time (RAT) (defined as the time duration for a node to stay awake) within the fixed Adaptive Scheduling (AS) period, so that nodes can change the length of the RAT in each operational cycle and be adaptive to the varying traffic load **Error! Reference source not found.**. Thus under high traffic load, the RAT will be prolonged to enable nodes to exchange more SCH frames, consequently transmitting more data in the Sleep period. Under low traffic load, the RAT will be shortened to enable nodes to sleep early. This is illustrated in **Figure 1**.

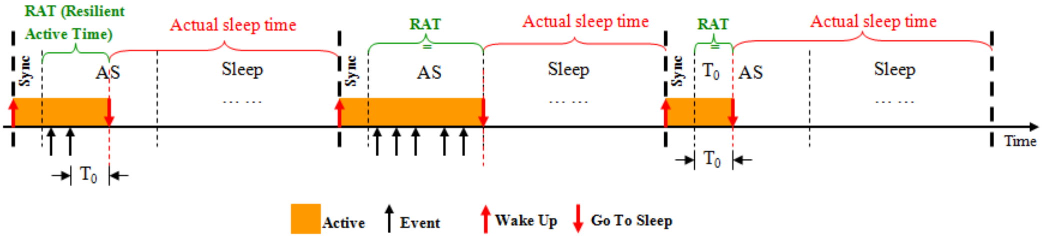

Figure 1: Adaptive Change of Resilient Active Time (RAT)

B. Enhanced Proportional Mapping Function

AS-MAC enhanced one-to-one proportional mapping function that determines wake-up and data transmission time of a pair of nodes in the Sleep period, and ensured collision-free Data-ACK packets transmission for two-hop scenario with such enhanced feature. It is illustrated in **Figure 2**.

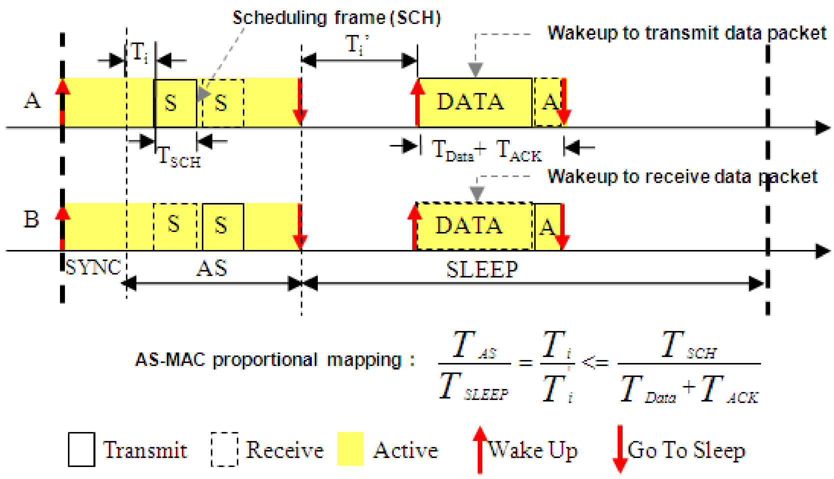

Figure 2: AS-MAC one-to-one proportional mapping function

C. *Dual-Role SCH Frame with Tracked Retry Numbers for Multi-Hop Forwarding*

When a node senses an event in the AS period, it employs a SCH frame to schedule the data transmission for the Sleep period. The next-hop node can broadcast one single SCH frame with dual-role to serve as CTS to the preceding node and as RTS to the succeeding node. By using the dual-role SCH frame, the number of access control packets needed for scheduling data transmission in multi-hop topology can be reduced almost by half. The number of SCHs needed to schedule *x*-hop data transmission is only *x+1* in AS-MAC while it needs *2x* frames in CSMA/CA. The scheduling overheads and the possibility of collisions can be much reduced.

In addition, AS-MAC includes two parameters in the header of the SCH -- *RTS_RetryNo* and *CTS_RetryNo*, in order to avoid redundant SCH packet transmission, thus reducing latency and energy consumption. It is illustrated in **Figure 3**.

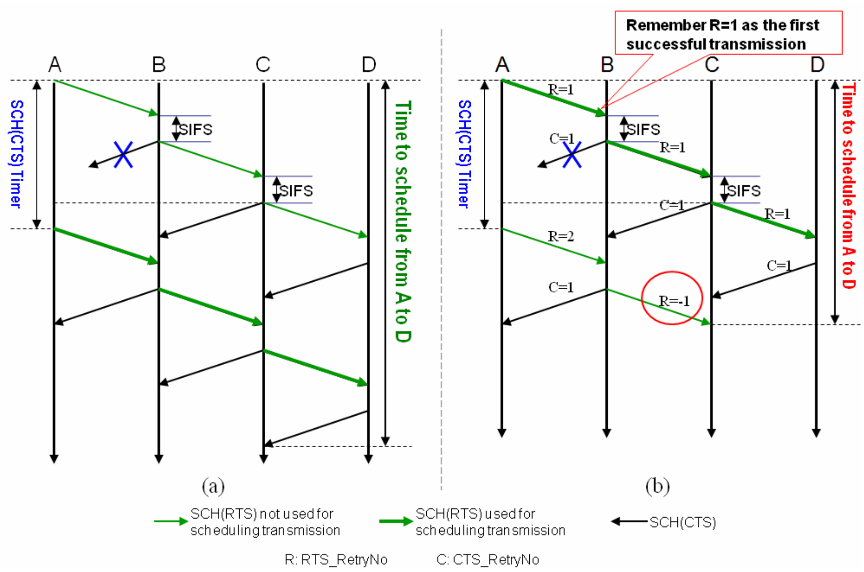

Figure 3: Forwarding SCH (a) DW-MAC, (b) AS-MAC

IV. Rationality of Ratio Parameters for AS-MAC

A. Theoretic Deduction of Rationale Ratio of T_{AS}/T_{Sleep}

AS-MAC protocol outperforms DW-MAC protocol from different facets of performance metric. One of improvements is in collision avoidance due to the enhanced one-to-one proportional mapping function from equation (1) to equation (2).

$$\frac{T_i}{T_i'} = \frac{T_{SCH}}{T_{Data}} = \frac{T_{AS}}{T_{SLEEP}} \qquad (1)$$

$$\frac{T_{AS}}{T_{SLEEP}} = \frac{T_i}{T_i'} <= \frac{T_{SCH}}{T_{Data}+T_{ACK}} \qquad (2)$$

We would say that this proportional mapping function further mitigates the probability of collision between data and ACK packet in multi-hop scenario and prevent data-ACK collision in two-hop scenario. To prove it, let's consider the worst case scenario when *n* SCHs are successfully transmitted from A to B in a sequence. The start time of i^{th} SCH is at the moment of T_i right after the AS period begins as in **Figure 4**

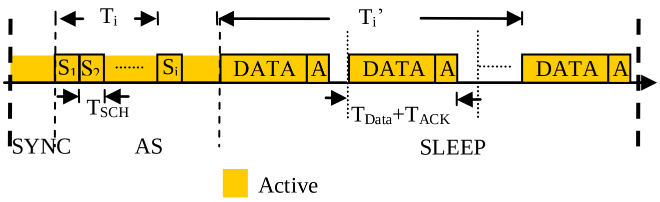

Figure 4. Condition for Collision-Free Data Transmission

In order for two successive SCHs to be transmitted successfully, they cannot overlap with each other, which needs: $T_{i+1} \geq T_i + T_{SCH}$. In the worst case scenario,

$$T_i = (i-1)T_{SCH} \qquad (3)$$

The i^{th} SCH corresponds to one successful Data transmission from A with one successful ACK transmission from B, which start at T_i' and require $T_{Data}+T_{ACK}$ to complete in the Sleep period, if the propagation delay is ignored. To prevent collisions, the successive transmission of a packet and an ACK cannot overlap as $T_{i+1}' \geq T_i' + T_{Data} + T_{ACK}$. Hence, we have:

$$T_i' \geq (i-1)(T_{Data} + T_{ACK}) \qquad (4)$$

From (3) and (4)

$$\frac{T_i}{T_i'} \leq \frac{(i-1)T_{SCH}}{(i-1)(T_{Data}+T_{ACK})} = \frac{T_{SCH}}{T_{Data}+T_{ACK}} \qquad (5)$$

The enhanced proportional mapping represented in (2) indicates that the ratio of $\frac{T_{AS}}{T_{SLEEP}}$ and $\frac{T_i}{T_i'}$ should be lesser than or equal to a constant value which is determined by three constant values at the right side of the equation (2). It also indicates that T_{Data} in equation (1) becomes too small to secure a collision-free data-ACK transmission in DW-MAC. AS-MAC, however, gets away this shortcoming by adding in T_{ACK} in the ratio calculation. It is equally saying that T_i' should be long enough in order to secure a collision-free data-ACK transmission. The resultant ratio from equation (2) will be used as guideline to set parameters T_{AS} *and* T_{SLEEP}.

With this mapping function plus MAC layer virtual sensing (RTS/CTS mechanism), AS-MAC can schedule data transmission with data-ACK collision-free in the Sleep period in two-hop scenario. For the multi-hop scenario, the data-ACK collisions will be mitigated with T_{ACK} being taken into the consideration in proportional mapping function.

From this mapping function, the maximum number of SCHs that can be issued in an AS period can be determined by $N_{SCH} = T_{SLEEP}/(T_{Data}+T_{ACK})$, where N_{SCH} is the maximum number of SCHs in an AS period, T_{SLEEP} is the duration of the Sleep period, which is a fixed parameter.

B. Experimental Results of Rationale Ratio

We evaluated AS-MAC using OMNET++ version 3.3 [11] under unicast traffic. We used the same network parameters as in [20] for our simulation of AS-MAC. **Table I** shows the networking parameters.

Table I: NETWORKING PARAMETERS

Bandwidth	20Kbps	Ch. Encoding Ratio	2
Tx Power	31.2mW	Tx Range	250m
Rx Power	22.2mW	Carrier Sensing Range	550m
Idle Power	22.2mW	Contention Window (CW)	64ms
Sleep Power	3 μW	**Size of ACK**	**10B**
SIFS	5ms	**Size of SCH**	**15B**
DIFS	10ms	**Size of Data**	**100B**
Retry Limit	5	State Transition Power	31.2mW
T_0	80ms	State Transition Time	2.47ms

The propagation delay is neglected. In order to compare fairly, we set the length of the operational cycle similar to that in the DW-MAC with the duration of Sleep period and AS period adjustable. The duration of Sleep period must satisfy condition (2) and at the same time the AS period should be as long as possible to adapt to high traffic load. Since transmission time is proportional to the size of data packet in transmission, we have:

$$\frac{T_{AS}}{T_{SLEEP}} \le \frac{T_{SCH}}{T_{Data}+T_{ACK}} = \frac{SizeofSCH}{SizeofData+SizeofACK} = \frac{15}{100+10} \approx 0.136 \qquad (6)$$

Durations of synchronization, AS Period and Sleep period are shown in **Table II**.

Table II: OPERATIONAL CYCLE CONFIGURATION

	T_{SYNC} (ms)	T_{AS} or T_{Data} (ms)	T_{SLEEP} (ms)	T_{Cycle} (ms)
DW-MAC	55.2	168.0	4241.8	4465.0
AS-MAC	55.2	527.9	3881.9	4465.0

In order to test AS-MAC protocol not only with ratios 0.136, but also with other ratio values, the following **Table III** tabulates T_{AS}, T_{SLEEP} and their corresponding ratio value. The experimental simulations are conducted using these parameters respectively.

Table III: Different T_{AS}/T_{SLEEP} ratios with step of 0.05s

Tcycle	=	Tsync	+	Tas	+	Tsleep	Ratio =	Tas/Tsleep	0.136
4.465	=	0.0552	+	Tas	+	Tsleep	Step=		0.05
Tas	0.6779	0.6279	0.5779	0.5279	0.4779	0.4279	0.3779		
Tsleep(s)	3.7319	3.7819	3.8319	3.8819	3.9319	3.9819	4.0319		
Ratio	0.1817	0.1660	0.1508	0.1360	0.1215	0.1075	0.0937		

The following Figure 5, 6 and 7 show the Average End-to-End delay, Packet Delivery Ratio (PDR) and Energy Consumption for different T_{AS}/T_{SLEEP} ratios respectively. Figure 5 shows that average end-to-end delay reach the lowest value when the T_{AS}/T_{SLEEP} ratio is in 0.136. For the ratio both greater than 0.136 and lesser than 0.136, their average end-to-end delay are longer than that of ratio with 0.136. Similarly, the Packet Delivery Ratio (PDR) reaches the highest value when T_{AS}/T_{SLEEP} ratio is in 0.136. With increasing and decreasing of the ratio, the PDR drop correspondingly. Energy consumption also presents a good performance for the ratio 0.136, and performance start to drop while walking away from the T_{AS}/T_{SLEEP} ratio 0.136.

We may conclude that for the given size of data package, control frame and ACK packet, a ratio 0.136 for T_{AS}/T_{SLEEP} is a rationale choice to achieve an optimized protocol performance. For the different data package size, the same approach applies to derive the new rationale ratio value.

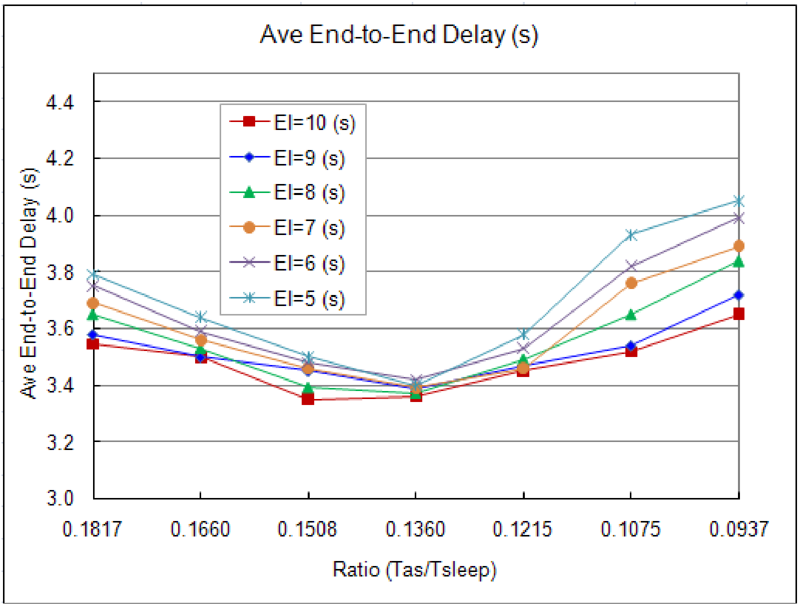

Figure 5: Average End-to-End Delay of different

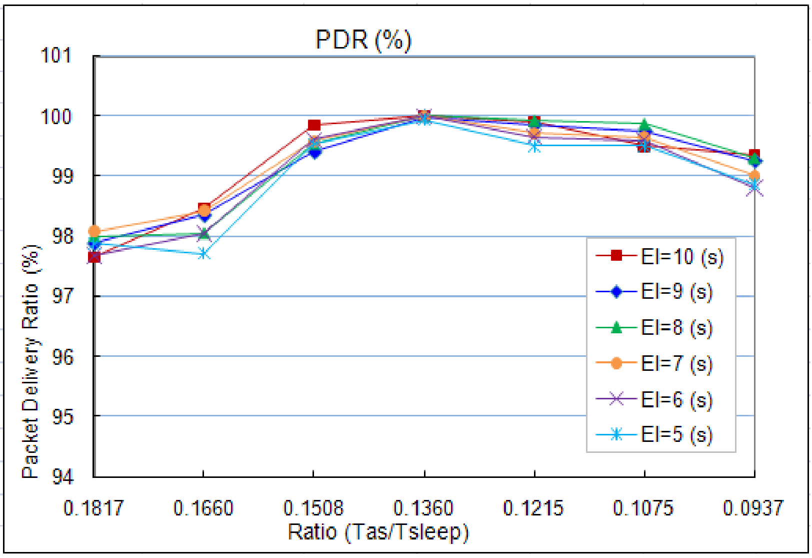

Figure 6: Packet Delivery Ratio (PDR) of different T_{AS}/T_{SLEEP} ratios

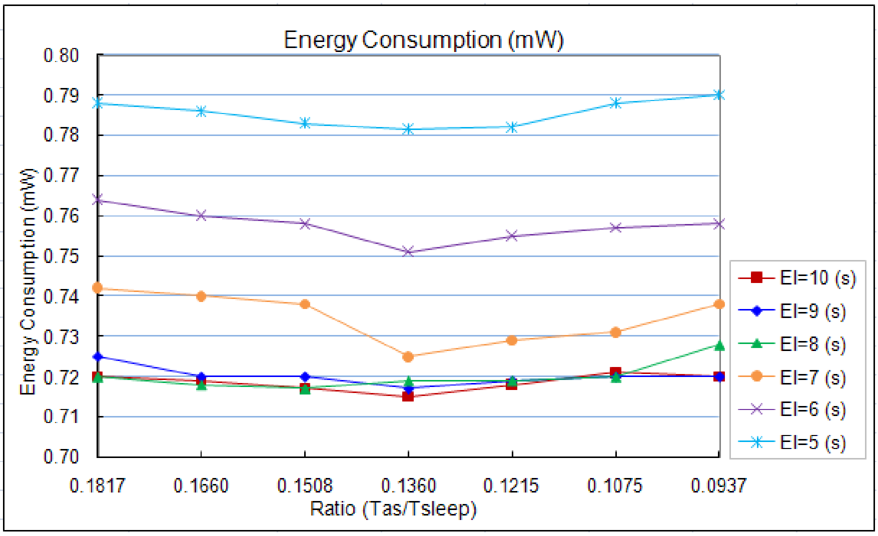

Figure 7: Energy Consumption of different T_{AS}/T_{SLEEP} ratios

V. Conclusion

It is nontrivial to achieve good performance in full spectrum of performance metrics at the same time. Selection of suitable parameters plays pivotal role for protocol to achieve good performance. Rationality of determining protocol parameters can be explained from both theoretic deduction and experimental results. This paper provides a theoretic deduction and experimental simulation results for the rationality of determining the T_{AS}/T_{SLEEP} ratio parameter for AS-MAC protocol. Although the size of data package, control frame and acknowledge packet determine T_{AS}/T_{SLEEP} ratio parameter for AS-MAC protocol, since data package size may vary from application to application, hence deriving different ratio parameters which in turn will result in different protocol performance, a theoretic deduction and experimental simulation results provide evidence and rationality for the parameters adoption, hence ensuring an optimized protocol performance.

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