PERFORMANCE EVALUATION OF IEEE 802.15.4 MAC WITH DIFFERENT BACKOFF RANGES IN WIRELESS SENSOR NETWORKS

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ABSTRACT

The IEEE 802.15.4 MAC (Medium Access Control) is a protocol used in many applications including the wireless sensor network. Yet the IEEE 802.15.4 MAC layer cannot support different throughput performance for individual nodes with the current specifications. However, if certain nodes are sending data more frequently compared to others, with the standard MAC, it is hard to achieve network efficiency. Therefore, we modified the IEEE 802.15.4 MAC and additionally proposed a new *State Transition Scheme*. By adjusting the minBE value of some nodes to a smaller value and by dynamically changing the value depending on the transmission conditions, we shortened the backoff delay of nodes with frequent transmission. It was observed through our simulations that the throughput of the node with a lower minBE value increased significantly, compared to nodes with the original BE range of 3 to 5. Also by the use of the *State Transition Scheme* the total network efficiency increased leading to increase in throughput performance.

1. INTRODUCTION

The IEEE 802.15.4 MAC [1] is designed for low-rate, low-power communication applications such as wireless sensor networks. However, the MAC design is inadequate to deal with when if certain nodes are sending data more frequently compared to others. In this case, with the standard MAC, it is hard to achieve network efficiency. To solve this problem we have modified the BE (Backoff Exponent) range in IEEE 802.15.4 MAC and adapted the *State Transition Scheme*. The fixed backoff range given in the IEEE 802.15.4 standard [1] limits the default value of the $minBE$ (minimum BE) as 3, and $aMaxBE$ (maximum BE) as 5, giving only the range of [0::2^3] to [0::2^5] for randomly selecting the actual backoff value. Until now there have been several studies about the backoff exponent of the IEEE 802.15.4 MAC.

Pang et al [2] proposed a new scheme dealing with the back-off exponent. His work increased the throughput performance by adjusting the BE value and exponentially decreasing the BE value upon successful transmission instead of instant decrease. Yet, [2] assumes that all nodes in the network follow the same BE range. In this work different throughput performance cannot be performed by individual nodes, therefore the network efficiency is not at its maximum. *Papadimitratos et al* [3] made an algorithm to estimate the BER (Bit Error Rate) of a wireless link. This estimation is used to determine the back-off time. The BER estimated from link estimation techniques were used to perform differentiation for nodes possible, by sacrificing fairness for throughput increase. Yet, finding the BER through link estimation is a complex process.

Yoon et al [4] proposed a scheme for service differentiation in IEEE 802.11e networks. In there work the main focus is also in modifying the backoff range. This paper proposes the similar scheme to the IEEE 802.15.4 MAC, so that individual nodes can react differently within a single network. Yet, we additionally adapt the *State Transition Scheme* to pursue efficient use of the differentiation. The modified MAC will help serve networks where different capacity must be supported to individual nodes. This modification will increase the network efficiency because nodes that send data frequently will have more opportunity to transmit compared to the nodes that remain idle.

2. STANDARD MAC OF IEEE 802.15.4

According to the standard of 802.15.4 [1], the 802.15.4 MAC is based on the CSMA-CA procedure. Fig. 1 shows the basic procedure of the 802.15.4 MAC. As seen in Fig. 1 the backoff algorithm is processed inside the CSMA-CA algorithm. The initial value of BE (Backoff Exponent) is given as $macMinBE$ and the system selects a backoff time from a random number between [0::$2^{BE} - 1$]. Once the backoff time is set, the system starts backoff and the slots in the CAP (Contention Access Period) of the superframe are skipped away. If a selected backoff is longer than the number of

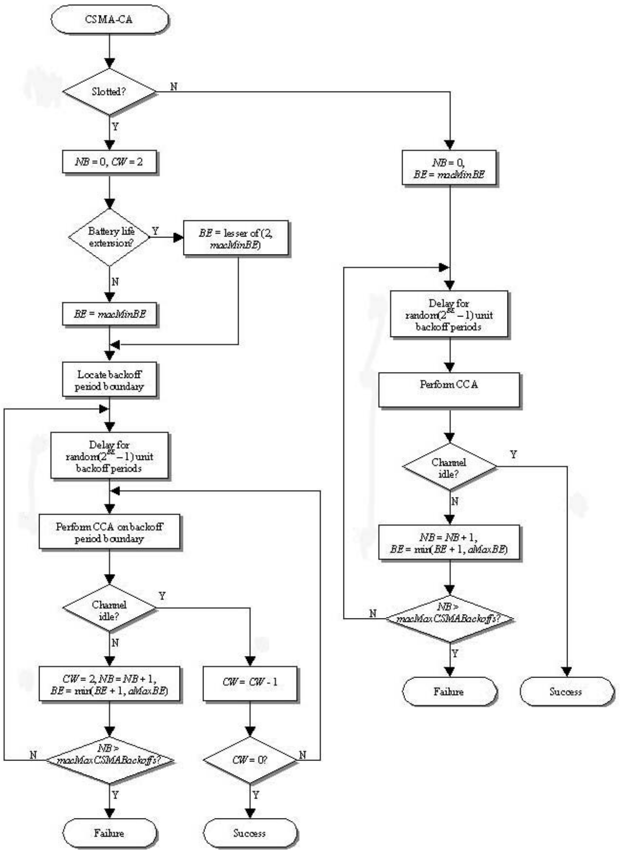

Fig. 1. The CSMA-CA Procedure in IEEE 802.15.4 Standard.

CAP that are left in the current superframe, the backoff is paused until the next superframe and continues the backoff on the CAP of the next superframe.

Fig. 2 shows the superframe structure in 802.15.4. A superframe is made of time slots between two beacons. The beacon, located on the two sides of superframes, is transmitted by the network coordinator to all nodes that are associated to it. It contains network information, frame structure and notification of pending downlink messages. The slots in a superframe is either a CAP or a CFP (Contention Free Period). The length of a superframe is controlled by the variable BO (Beacon Order) and the length of CAP is represented by SO (Superframe Order). The CFP consists of GTS (Guaranteed Time Slots) to various nodes. A GTS may occupy more than one slot. Information about GTS for various nodes is given in the beacon and all GTS transmissions must end before the start of the beacon transmission. All the transmissions in CAP must end before the start of CFP and start of beacon transmission.

After the backoff time is over, the system performs CCA (Clear Channel Assessment) to check if the channel is busy or not. If the channel is sensed busy, the value of BE is increased by one and a new random number is selected from the new range for another backoff period. If the channel is sensed idle for two consecutive CCAs (*i.e.* when CW=0) the channel is considered idle and the system can start transmission.

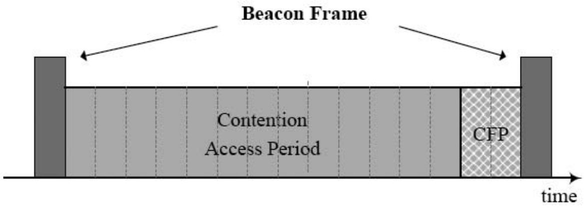

Fig. 2. Superframe Structure in 802.15.4.

We suggest changes to the backoff algorithm of the IEEE 802.15.4 standards [1] in this paper. Wee see limitations to the standard caused by the static default $macMinBE$ value, which is given as 3. Our main ideas and modifications will be shown in the following sections.

3. MAC MODIFICATIONS

3.1. Backoff Exponential Range Modifications

To support different capacity to individual nodes in a wireless sensor network, we propose modifications to the MAC layer considering the value of the $minBE$. The 802.15.4 standard [1] states that the BE value is set to a random number between the range of two variables, $minBE$ and $aMaxBE$. The $aMaxBE$ indicates the maximum number of the backoff exponent. This value is limited to 5 in the standard. The $minBE$, which indicates the minimum value of the BE, can be set to a number between 0 and 3. Yet, the default value is given as 3. To give differentiation to individual nodes we suggest that the minimum value of the IEEE 802.15.4 MAC be flexible to changes. If the BE value is decremented to a value less than the default value 3, the lower boundary of the possible backoff value will decrease also. It will shorten the waiting time when CCA detects the channel busy or when a packet collides with a different packet in the channel. This gives a higher chance of selecting a shorter backoff time. This makes the node try the CCA more frequently, leading it to a higher possibility of making a successful transmission. Because of this the throughput will increase significantly compared to other nodes with longer waiting times.

3.2. State Transition Scheme

In the MAC modifications, we let the value of the $minBE$ be a number between 1 and 3. The value of the $minBE$ changes flexibly as the condition of the node changes. As

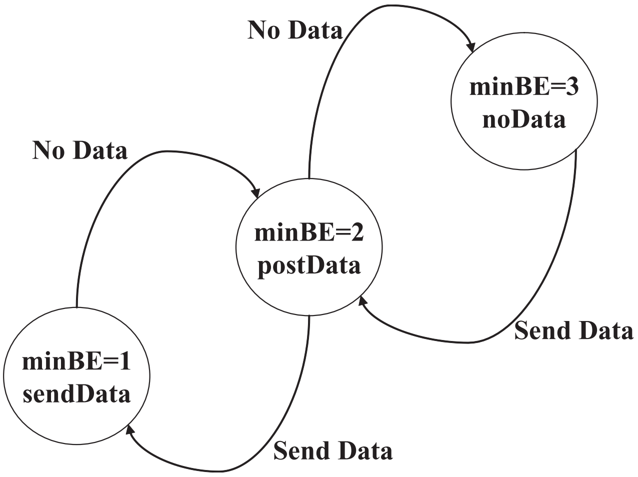

Fig. 3. State Transition Scheme.

seen in Fig. 3, each node has three states, $noData$, $postData$, $sendData$, with each state having the default $minBE$ value of 3, 2 and 1 respectively.

Step 1
The nodes are initialized to the standard BE range (minBE=3) upon coordination. The state is initialized to $noData$.

Step 2
When the node detects that a data packet is ready for transmission, the node changes it's state to $postData$ state and modifies minBE=2. The lower minBE value will give the node a higher chance of selecting a lower backoff value and quickly transmit the data packet.

Step 3-1
After two continuous transmission of data packets without any discontinuance, the state changes to the $sendData$ state and the minBE is modified to 1.

Step 3-2
After two continuous beacon frames with no transmission of data packets, the state changes to the $noData$ state and the minBE is modified to 3.

Step 4
When a node is in the $sendData$ state and no data packets are transmitted for two continuous beacon frames the node changes it's state to $postData$ state and modifies minBE to 2.

Fig. 4. Basic Steps of the State Transition Scheme.

Fig. 4 shows the basic steps of the *State Transition Scheme*. The three state are switched dynamically via Fig 4. The nodes are requested to count the number of idle beacon frames (with no transmission) and the number of successful transmissions within a beacon frame, before the CCA process. By counting the numbers we can allow the nodes with more data to transmit to a higher priority in the network. The *State Transition Scheme* will not make additional fairness problems because if a node has nothing to send any more it increases the $minBE$ so that it can be excluded from the high priority nodes (Step 3-2, Step 4). The throughput performance of nodes with differentiated $minBE$ values differ as Eq. 1.

$$minBE_\alpha : minBE_\beta = 2^{minBE_\beta} : 2^{minBE_\alpha}, \qquad (1)$$

where $minBE_\alpha$ and $minBE_\beta$ are the minBE values of differentiated nodes. This is derived in *Kim et al* [5].

4. SIMULATION RESULTS

We used the NS-2 [6] simulator and modified the NS-2 802.15.4 MAC simulator made by SAMSUNG and CUNY [7] for our simulations. Tab. 1 shows the specifications of our simulations.

Table 1. Parameters Used in Simulation

Parameter	Value
Traffic Type	CBR Traffic
Packet Size	90 Bytes (Including Header)
Data Interval	0.001 ms
Number of Nodes	3-16 (Including Coordinator)
Routing Type	AODV
Topology	Star Topology
Antenna Type	Omni-Directional Antenna
BO Value	3
SO Value	3

Fig. 5 shows the throughput performance for a single node. $TotalNetwork$ shows the total aggregate throughput performance of the network in total, $minBE = 1$ shows the throughput of the node with the modified MAC with the minBE at 1 (*i.e.* BE range of 1 through 5). $minBE = 3$ shows the throughput performance of a single non-modified node with the BE range of 3 through 5. From the figure it can be seen that the modified node with a lower minBE value has higher throughput than a node with no modifications. As derived from Eq. 1, we note that the node with the minBE value of 1 has about 4 times better performance as in throughput performance than the node with minBE value of 3. This shows that the modified node has much higher priority than the non-modified node.

Fig. 6 shows the ratio of the throughput performance of the modified node over the total aggregate throughput of the network. It stays at a value around 74-77% which takes up, in some cases, more than three fourths of the total network capacity. This result is similar to the estimations using Eq. 1. We notice from Fig. 5 and Fig. 6 that the modified node takes up a high portion of the total network capacity. As the number of nodes increases, the throughput for a single

Table 2. Throughput Performance of Network with Many Differently Differentiated Sensor Nodes (Kbps)

Number of [1:5]	Throughput of [1:5]	Number of [2:5]	Throughput of [2:5]	Throughput of [3:5]	Total Throughput
1	61.785	1	40.337	2.268	122.485
1	61.890	2	18.449	3.084	122.776
1	59.798	3	11.368	3.608	115.841
2	28.688	1	35.468	2.249	108.754
2	28.442	2	16.334	2.481	104.761
2	27.752	3	13.797	2.556	109.889
3	17.778	1	33.118	2.350	100.753
3	17.336	2	16.550	3.245	101.247
3	15.634	3	10.368	5.390	101.567

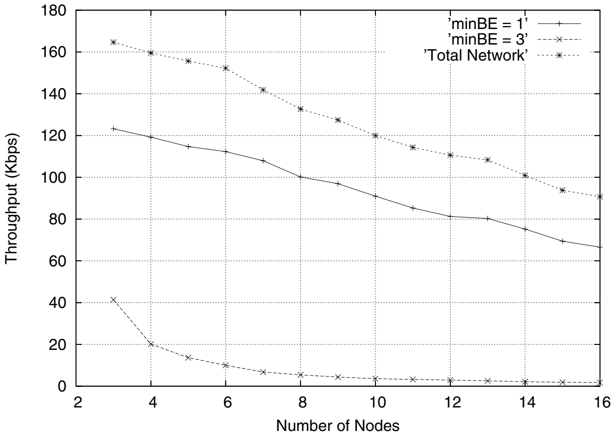

Fig. 5. Throughput of [1:5] node (kbps).

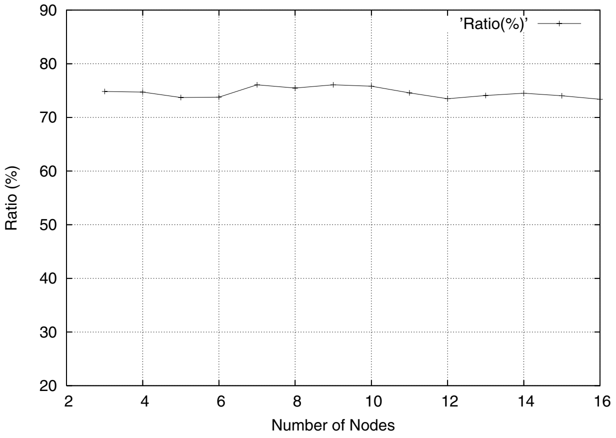

Fig. 6. Ratio of [1:5] node Throughput over total network throughput (%).

node with $minBE = 3$ decreases. This is because the total available throughput for all nodes with $minBE = 3$ always stays at a certain ratio but the number of nodes increases, leading the nodes to share a limited throughput.

Fig. 7 and Fig. 8 show the results for the same simulations done in Fig 5 and Fig. 6, but done with a node modified to a minBE value of 2, *i.e.* the node having back-off exponent range of 2 through 5 ($minBE = 2$). In the two figures, it is seen that although the throughput is not as high as the node modified to have minBE as 1, it still shows much higher throughput performance than that of a non-modified node. This can also be analyzed by Eq. 1. Analysis estimates that 50% of the capacity will be concentrated to the node with $minBE = 2$, and our simulations also show similar results of values abound 50-55%.

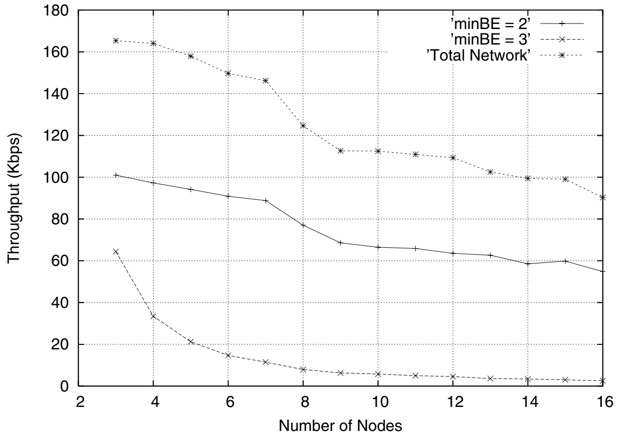

Fig. 7. Throughput of [2:5] node (kbps).

Tab. 2 shows how the nodes react when many differently differentiated nodes are placed. The total number of nodes used in this simulation is 10, [1:5] and [2:5] each indicate nodes with $minBE$ of 1 and 2, respectively. The throughput in kbps indicate the throughput performance of a single node. Tab. 2 shows that the nodes in different states surely support high throughput than non-modified nodes even when

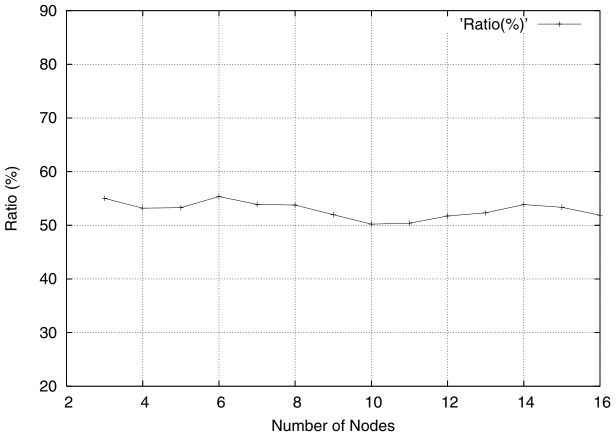

Fig. 8. Ratio of [2:5] node Throughput over total network throughput (%).

different situations are mixed together. This shows that the sensor, given the *State Transition Scheme*, can react normally within a wireless sensor network.

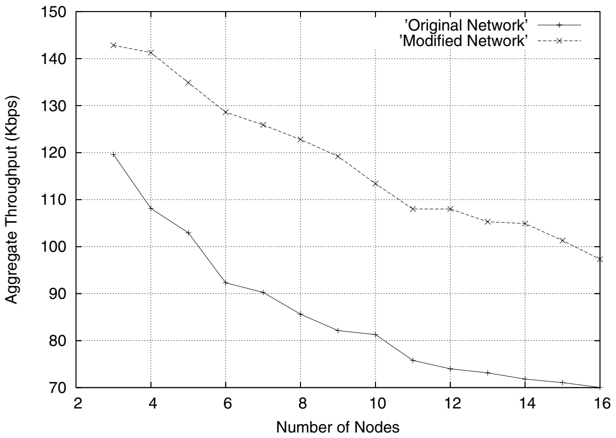

Fig. 9. Throughput comparison of Original Network and Modified Network (kbps).

Fig. 9 shows the comparison between a normal IEEE 802.15.4 network and a network modified to our scheme. The modified nodes in our experiment change automatically depending on their current status (See Fig. 3). The network using the *State Transition Scheme* shows more than 45% increase in some conditions. From this it can be said that the *State Transition Scheme* can increase the efficiency of a wireless sensor network to a higher level, leading to increase in throughput performance.

5. CONCLUSION

In this paper we have proposed modifications to the IEEE 802.15.4 MAC. Modifications were made to the range of the BE value of the original MAC. The original range for BE selection was 3 through 5. Yet, to differentiate the performance, we have changed some of the nodes' $minBE$ to a lower value. The change let the modified node take advantage in transmitting data compared to the non-modified nodes, resulting higher throughput performance for the modified node. By implementing the *State Transition Scheme*, we could increase to total possible capacity of the network by using the medium of the wireless network more efficiently. In the future work, more analysis on the characteristics of the IEEE 802.15.4 MAC layer will be done. Considerations about other tradeoffs of modifying the MAC including energy consumptions and delays will be part of the research. Also our MAC modification techniques will be applied to other application programs other than the legacy itself. This will increase the effectiveness of the MAC modifications and the *State Transition Scheme* we have proposed.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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