Performance Analysis of IEEE 802.15.4 868MHz, 915MHz and 2.4GHz Physical Schemes in 6LoWPAN

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***Abstract*— In the IEEE 802.15.4 CSMA/CA MAC layer protocol, there are different trade-off points between the number of nodes competing for the medium and the network capacity. In this paper, we investigate the data transmission performance corresponding to the number of competing nodes in IEEE 802.15.4-based MAC and PHY layers using 6LoWPAN protocol stack. Analysis of the transmission performance by each type of PHY schemes over different working frequency shows that the parameters in these layers play a critical role in determining the overall performance in 6LoWPAN. The goal of this research is to compare the transmission efficiency using exact formulae in un-saturated IEEE 802.15.4 Based sensor networks under varying numbers of competing nodes. Analysis results show that the O-QPSK modulation scheme in 2.4GHz PHY scheme has higher transmission probability and more efficient throughput in 6LoWPAN.**

***Keywords*— 6LoWPAN, IEEE 802.15.4, CSMA/CA**

1. INTRODUCTION

The IEEE 802.15.4 [8] standard defines the physical and link layers for low-rate Wireless Personal Area Networks (LR-WPAN), used in wireless sensor networks applications with strong energy consumption constraints. The physical layer comprises three principal frequency bands allowing 49 channels: 16 channels in the 2450 MHz for the ISM (Industrial Scientific Medical) band, 10 for North America and 1 channel in the 868 MHz band for Europe [8]. The band of 2450 MHz operates at law data rates of 250 kb/s while the bands of 915 MHz and 868 MHz operate at 40 kb/s and 20 kb/s respectively.

In wireless sensor networks, the transceiver in the 868/915 MHz band is more suitable when low data rate transmission are used between sensor nodes. Furthermore it presents a longer range than that of the 2450 MHz band for a given link budget. The objective of our work is to compare the transmission efficiency of 802.15.4 standard for the 868 MHz, 915MHz and 2.4GHz band under varying numbers of competing nodes, which is not yet reported in the literature. Furthermore, the performance to transmission IPv6 over Low-power Wireless Personal Area Networks (LoWPAN) under three different MAC PHY layers is also investigated in this paper. In IPv6 over LoWPAN (6LoWPAN) [1][9] is difficult to implement because the size of IPv6 packets is much larger than the packet size of IEEE 802.15.4 data link layer. In order to make it possible, the IETF 6LoWPAN working group introduces the adaptation layer between network and data link layers. It provides header compression to reduce transmission overhead, fragmentation and reassembly of IPv6 packet. It can also be involved in routing decisions, and the routing scheme in 6LoWPAN [6] can be divided into two different methods. First, in the mesh-under method, the routing decision is taken in adaptation layer. Second, the route-over method makes the routing decision in network layer. Mesh-under and route-over can be considered as end-to-end and hop-by-hop transmission respectively. Although hop-by-hop fragmentation and reassembly generate more delay but achieve better fragment arrival ratio. Whereas end-to-end scheme has less latency, but fragment loss has high probability. Hence, we analyse the performance and find the probability of successful transmission only for mesh-under schemes.

In WSN modellings, [2] presented a similar analytical model to predict energy consumption as well as the throughput of saturated and

unsaturated 802.15.4 networks, based on which some design guidelines can be derived. In order to address system goodput and energy efficiency enhancement. [3] study packet size optimization for IEEE 802.15.4 networks. Taking into account of the CSMA-CA contention, protocol overhead, and channel condition, analytical models are proposed to calculate the goodput and the energy consumption. In [4], the authors try to analyse the complete CSMA/CA in IEEE 802.15.4. First, to analyse the performance of the slotted CSMA/CA of IEEE 802.15.4 by integrating the discrete-time Markov chain models of the node states and the channel states; and then, extend the models by adopting a modification to the CAP. The extended models could be used to analyse the performance of the un-slotted and slotted CSMA/CA strategy. In non beacon-enabled mode, [5] build a process chain to model un-slotted CSMA/CA mechanism. However, the back-off procedure is not only a Markov chain but also the back-off time counter is an accumulation which value depends on how many times the node has tried to access the channel without success. According to the proposed process chain and mathematical model, the distribution of traffic changes has been estimated when different load are offered to the network. Moreover, the proposed model can evaluate the proper size a packet to improve the success probability.

In 6LoWPAN experimental [6], they perform an analytical comparison between route-over and mesh-under these two schemes in terms of the packet/fragment arrival probability, the total number of transmissions and the total delay between source and destination.

The contribution of this paper is that we use the Markov chain tool to analyse the MAC performance of un-slotted CSMA/CA in IEEE 802.15.4; Moreover, we attempt to find the probabilities of MAC transmission in the different operating frequency bands (868/915 MHz and 2.4 GHz). And these probabilities can substitute into 6LoWPAN routing schemes modelling. Finally, we can derive the probabilities of routing scheme with different frequency bands. These results can be used to evaluate what the frequency bands is advantage in 6LoWPAN.

The rest of the paper is organized as follows. Section 2 presents a description of the 6LoWPAN and its routing schemes. In Section 3, we present the description of the CSMA/CA in IEEE 802.15.4. Section 4 discusses our analysis model in un-slotted IEEE 802.15.4 CSMA/CA mechanism. Evaluation results for transmission probability and 6LoWPAN throughput are presents in Section 5. Finally, Section 6 concludes the paper.

2. ROUTING SCHEME IN 6LOWPAN

As mentioned, 6LoWPAN divides routing schemes into mesh under and route over. The distinction is based on which layer of the 6LoWPAN protocol stack is in charge of routing decisions; in route over they are taken at the network layer, and in mesh under at the adaptation layer. The main difference between these two schemes depends on how the packets or fragments are processed before being forwarded.

2.1. Mesh-under

In mesh-under scheme, an IPv6 Packet is fragmented into a number of fragments at adaptation layer. And then, these fragments will be sent to the next hop by mesh routing and eventually reach to the destination. If all fragments are gathered at the destination node successfully, then the adaptation layer of destination node starts reconstruction process. These all fragments reassemble to original IP packet. In case of any fragment lost in forwarding process, the whole IP packet cannot be reconstructed. The all fragments of the IP packet are retransmitted form source node to destination node.

2.2. Route-over

When an IPv6 Packet is fragmented by the adaptation layer, fragments will be sent to the next hop based on routing table information. If all fragments are received successfully at next hop and they are part of the same IP fragmented packet. First, the adaptation layer needs to reassemble them in order to reconstruct the original IP packet. The reconstruction process starts only when the last fragment arrives. Once reconstructed, the IP packet will be sent to the network layer. If the IP packet has to be forwarded, it will be sent back to the adaptation layer. Finally, the IP packet will be fragmented again and these fragments will be delivered to the next-hop. If any fragment lost in this forwarding process, the retransmission execute in one hop distance.

3. OVERVIEW OF CSMA/CA MECHANISM IN IEEE 802.15.4

As discussed in previous studies [2][3][4], the CSMA/CA procedure work as follows. First, a node with a packet need to backoff for a random number of backoff slots before channel sensing.

The range of random backoff window (BW) is from [0, $2^{macMinBE}$-1]. Here *macMinBE* is the minimum value of the backoff exponent (BE) has the default value is 3. When backoff counter reaches 0, the node performs channel sensing immediately.

The random backoff and the following channel sensing use to decrease the probability of collisions and ensure the channel is clear that a node can access it. The contention window in unslotted CSMA/CA is one backoff period. (In slotted CSMA/CA, which perform two channel clear assessments before transmission.) If the channel is detected to be busy, BE is increased by 1, and the new backoff stage begins before channel sensing. This process is repeated until BE equals upper bounded *aMaxBE* (maximum value of BE, default is 5), then the BE is frozen at *aMaxBE*. When the number of backoff stage is equal to *macMaxCSMABackoff* (the default value is 4), the node access channel is failure. Fig. 1 illustrates the steps of CSMA/CA algorithm.

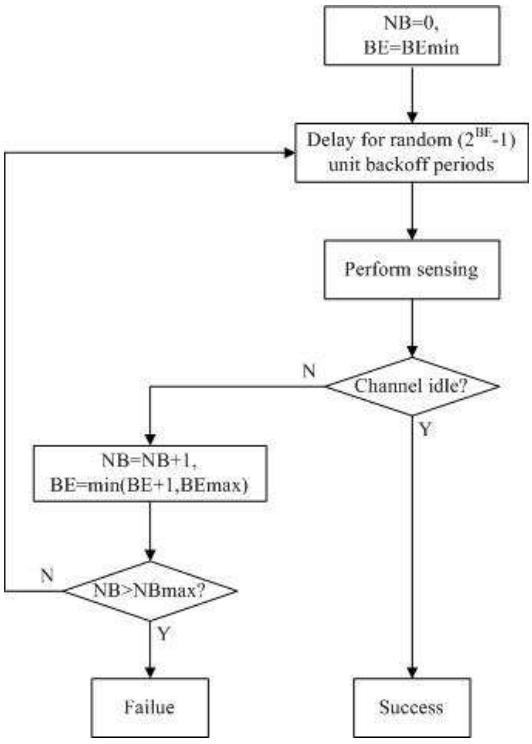

Fig. 1 IEEE 802.15.4 CSMA/CA algorithm

4. MARKOV CHAIN MODEL FOR UNSLOTTED CSMA/CA MECHANISM

For the analysis, we construct a two-dimensional discrete-time Markov chain to model the slotted CSMA/CA mechanism is shown in

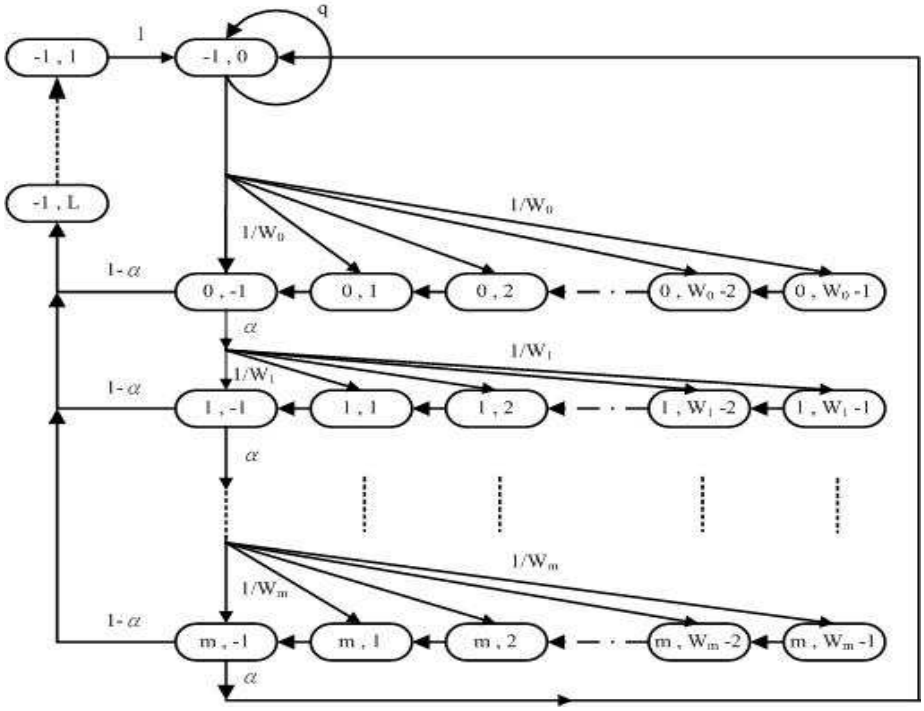

Fig. 2 two-dimensional discrete-time Markov chain to model the slotted CSMA/CA mechanism

Fig. 2. Define the state as {$nb(t)$, $bw(t)$}; $nb(t)$, $bw(t)$ as the stochastic process representing the backoff stage and the backoff counter at time slot t, respectively. Here $nb(t) \in [0, m]$, m is determined by *macMaxCSMABackoff*; $bw(t) \in [0, W_i\text{-}1]$. And when the $nb(t) = -1$ is the transmission stage. According to the protocol, the duration of the backoff window is

$$W_i = 2^{macMinBE} 2^{min\{aMaxBE - macMinBE, i\}}, i \in [0, m]$$

In Fig. 2, α is the probability that the channel is found busy. Where L is the numbers of time slot that packet in transmission durations. Hence, the length of a transmission period must equal to the length of packet. And q is defined as the probability that the user still in the idle state in the next time slot.

Let the stationary probabilities of the Markov chain be $b_{n,b} = P\{(nb(t), bw(t)) = (n, b)\}$. Note that backoff counter reaches 0, the node enters CCA state immediately. Hence, $b_{n,0}$ has a same value as $b_{n,-1}$. From the Markov chain model in Fig. 2, we obtain

$$b_{n,-1} = \alpha^n b_{0,-1} \quad , n \in [1, m] \quad \text{.....(1)}$$

$$b_{-1,L} = (1 - \alpha^{m+1}) b_{0,-1} \quad \text{.....(2)}$$

$$b_{-1,0} = \frac{b_{0,-1}}{1 - q} \quad \text{.....(3)}$$

$$b_{n,b} = \frac{W_n - b}{W_n} \alpha^n b_{0,-1}, \quad n \in [1, m], b \in [1, W_n - 1] \quad \text{.....(4)}$$

$$b_{0,b} = \frac{(W_0 - b)(1 - q)}{W_0} b_{-1,0} = \frac{W_0 - b}{W_0} b_{0,-1}, \quad b \in [1, W_0 - 1] \quad \text{.....(5)}$$

The sum of probabilities of all the states should equal to 1, we have

$$b_{-1,0} + \sum_{l=1}^{L} b_{-1,l} + \sum_{n=1}^{m} b_{n,-1} + b_{0,-1} + \sum_{n=0}^{m} \sum_{b=1}^{W_n - 1} b_{n,b} = 1 \quad \text{.....(6)}$$

Where τ is the Probability that a node attempts carrier sensing, we get

$$\tau = \sum_{n=0}^{m} b_{n,-1} \quad \text{.....(7)}$$

Assume the system have N nodes. From the [2], the probability that the channel busy in CCA is

$$\alpha = \left[1 - \frac{1}{1 \cdot \left(1 + \frac{1}{1 - (1 - \tau)^N} \right)} \right] \cdot \left(1 - (1 - \tau)^{N-1} \right) = \frac{1 - (1 - \tau)^{N-1}}{2 - (1 - \tau)^N} \quad \text{.....(8)}$$

According to the Fig. 2 Markov chain model, we can get the probability to enter transmission stage is

$$P_{mac-tx} = \tau \cdot (1 - \alpha) \quad \text{.....(9)}$$

We assume that the link is single-path and the channel condition in every hop has same transmission probability. In this paper, we only focus on the performance on 6LoWPAN mesh-under routing scheme. From (9), the probability of 6LoWPAN mesh-under routing schemes, we obtain,

$$P_{success}^{mu} = \left\{ \left[\sum_{i=1}^{k} (P_{mac-tx})(1 - P_{mac-tx})^i \right]^j \right\}^h \quad (10)$$

The equation (10) is the probability of success transmission in mesh-under routing technique. Let k is the number of retransmission, n is the number of fragments with hop counts h. Each fragment sends from source to the destination in h number of hops. Thus, the transmission probability decreases gradually after h hops transmission route-path.

5. EMULATION RESULTS

In this section, we present the numerical performance analysis for IEEE 802.15.4 under the 6LoWPAN. A probabilistic model checker was emulated by PRISM [7]. The three types of PHY in IEEE 802.15.4 are shown in Table 1.

TABLE 1, THE LIST OF THREE PHY SCHEMES OF IEEE 802.15.4

	868 MHz	**915 MHz**	**2.4 GHz**
Channel Numbering	0	1 to 10	11 to 26
Area	Europe	America	Global

TABLE 2, NUMERICAL EVALUATION PARAMETERS [8]

Numbers of competing nodes *N*	3, 5, and 7	
macMinBE	3	
aMaxBE	5	
macMaxCSMABackoff	4	
Operating Frequency Bands	868/915 MHz	2.4GHz
Modulation	BPSK	O-QPSK
Bit rate	20 and 40 (kb/s)	250 (kb/s)
Symbol rate	20 and 40 (ksymbol/s)	62.5 (ksymbol/s)
aUnitBackoffPeriod (The number of symbols forming the basic time period used by the CSMA-CA algorithm.)	20 symbols	
1. **802.15.4 Minimum data length**= 15 bytes	6 (slots)	2 (slots)
2. **Compressed 6LoWPAN Header**=25 bytes	10 (slots)	3 (slots)
3. **Compressed 6LoWPAN with 20 bytes payloads**=45 bytes	18 (slots)	5 (slots)
4. **Uncompressed 6LoWPAN Header**=80 bytes	32 (slots)	8 (slots)
5. **Uncompressed 6LoWPAN with 20 bytes payload**=100 bytes	40 (slots)	10 (slots)
6. **802.15.4 Maximum data length**=133 bytes	54 (slots)	14 (slots)

Since the performance analysis in this paper focuses on a single hop scenario. Thus, we assume that all competing nodes generate same length of packets. Furthermore, the selected PHY scheme has the same data rate and symbol rate. 868/915 MHz and 2.4 GHz frequency bands are 1 and 4 number of data bits per symbol respectively. The time slot is the smallest unit of packet length in this study. Table 2 shows the related numerical evaluation parameters. (Note that, a backoff slot is equal to 20 symbols.) Six type of packet length have been defined for 868/915 MHz and 2.4 GHz PHY schemes from number 1 to 6 in Table 2.

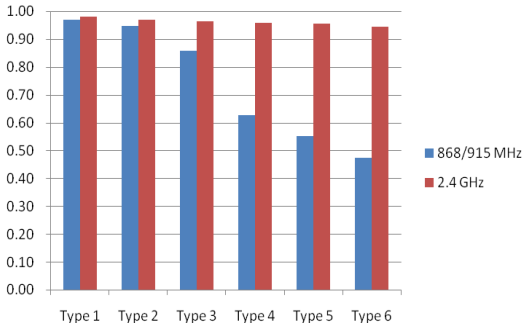

Fig. 3 The probability of transmission with 6 types of packet length in both 868/915 MHz and 2.4GHz PHY schemes, and the number of competing nodes is 3.

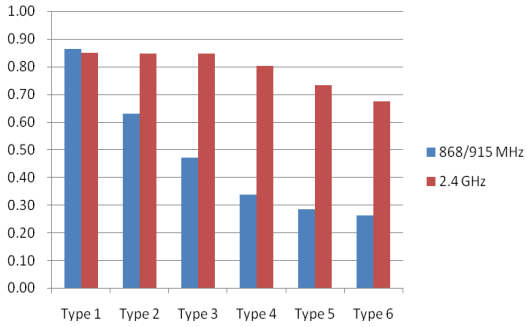

Fig. 4 The probability of transmission with 6 types of packet length in both 868/915 MHz and 2.4GHz PHY schemes, and the number of competing nodes is 5.

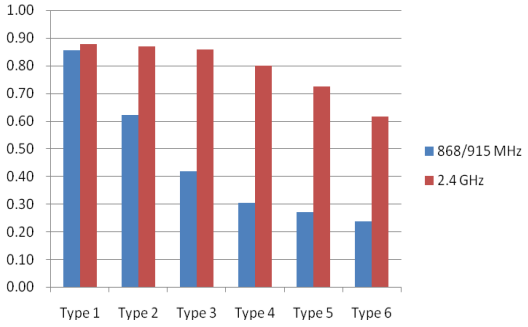

Fig. 5 The probability of transmission with 6 types of packet length in both 868/915 MHz and 2.4GHz PHY schemes, and the number of competing nodes is 7.

From Fig 3 to 5, present the probability of Pmac-tx with six types of packet length in 868/915MHz and 2.4GHz PHY schemes with the 3, 5, and 7 competing nodes respectively.

There results lead to the observation that the probability decreases by increasing packet length

in different level between 868/915MHz and 2.4GHz PHY schemes. 868/915 MHz PHY scheme is more sensitive by the packet length than 2.4GHz PHY scheme. The transmission probability became very low when the packet length reaches the maximum packet size.

The reason is that, the number of bits per symbol in 868/915 MHz PHY scheme is only one quarter of the number of bits per symbol in 2.4 GHz PHY scheme. As a result, it might be consumed more slot time to occupy channel in transmission by using 868/915 PHY scheme, more slot time is occupied by one certain node when both packet length and number of competing nodes are large. Thus, remain competing nodes cannot access channel successfully within *macMaxCSMABackoff* period. Similarly, the transmission probability is also decreased by increased number of competing nodes.

The analytical result shows that the 2.4 GHz PHY scheme has higher transmission probability than 868/914 MHz PHY scheme when packet length and the number of competing nodes are large. In 6LoWPAN, the fragmentation scheme divides original IPv6 packet into several smaller mesh packets. Analysis shows that packet length control is one of solutions that to enhance the performance of 6LoWPAN within a large number of competing nodes.

6. CONCLUSIONS

The goal of this research is to compare the transmission efficiency using exact formulae in un-saturated IEEE 802.15.4 Based sensor networks under varying numbers of competing nodes. We evaluate several critical PHY/MAC layer design and their impact on the performance of an IEEE 802.15.4-based 6LoWPAN. In particular, we consider the impact between the combination of MAC/PHY and the number of competing nodes using un-slotted CSMA/CA in 868MHz, 915 MHz and 2.4GHz. Analysis results show that the 2.4GHz PHY scheme has higher transmission probability and more efficient performance in 6LoWPAN.The future work will investigate the transmission performance in error-prone channel condition in order to improve the accuracy of available bandwidth in both 6LoWPAN route-over and mesh-under routing schemes.

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