MAC Throughput Limit Analysis of Slotted CSMA/CA in IEEE 802.15.4 WPAN

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***Abstract*— IEEE 802.15.4 low-rate Wireless Personal Area Networks (WPAN) are expected to provide ubiquitous networking between small personal/home devices and sensors with low power consumption and low cost features. The technology employs special CSMA/CA to save power consumption for battery-powered small or portable WPAN devices. In this letter, we present a new model for the slotted CSMA/CA of IEEE 802.15.4 Medium Access Control (MAC) and evaluate its throughput limit in order to grasp the characteristics of IEEE 802.15.4 WPAN.**

***Index Terms*— CSMA/CA, IEEE 802.15.4, MAC, Throughput, WPAN.**

I. INTRODUCTION

IN the beacon-enabled mode of IEEE 802.15.4 Medium Access Control (MAC), a Wireless Personal Area Networks (WPAN) coordinator broadcasts beacons to the devices (DEV) at regular superframe intervals to maintain synchronization of the devices [1]. A superframe interval comprises the active and inactive duration, and the active part consists of contention access period (CAP) and contention free period (CFP). Devices exchange time-sensitive data streams in CFP, while devices contend for transmission of asynchronous data in CAP. IEEE 802.15.4 employs specially designed slotted CSMA/CA-based MAC during CAP of a superframe to save power consumption, which is an essential requirement for battery-powered small or portable WPAN devices. The rationale of the slotted CSMA/CA mechanism is to minimize the power-consuming intervals for channel sensing and backoff.

Recently, there have been simulation-based studies focusing on performance of beacon-enabled MAC [2], and on feasibility of low-rate WPAN with several application scenarios [3], and analysis study on beacon-enabled WPAN [4], [5]. Although typical traffic load and duty cycle is small in low rate-WPANs, we may not preclude the possibility of future large-scale deployment of WPANs. In addition, there is a clear distinction between CSMA/CA of IEEE 802.15.4 and that of the others. In this sense, it is vital to present a new model with the theoretical limit. In this letter, we present a new analytical model for slotted CSMA/CA of IEEE 802.15.4 MAC, and study its performance limit. The organization of this letter is as follows: In Section II, we describe the MAC functions of IEEE 802.15.4. Then, we formulate a Markov chain for the MAC and derive the performance limit in Section III. Finally, we conclude in Section IV.

II. MAC FUNCTIONS OF SLOTTED CSMA/CA

In slotted CSMA/CA of IEEE 802.15.4, three counters are maintained in each device for channel access control. NB is the number of backoff trials (backoff stage) for the transmission of a frame. BE is the backoff exponent to generate a random backoff duration for which a device has to wait before attempting carrier sensing. CW is the value of the contention window slots for clear channel assessment (CCA) after the random backoff duration.

Let k denote the backoff stage NB of a device. And, let $w_k = 2^{BE_k}$ be the backoff window at backoff stage k of a device, where backoff exponent BE_k = 3, 4, 5, 5, and 5 for $0 \leq k \leq m$ (m = 4) [1]. Initially ($k = 0$), a device with a pending frame for transmission selects a random backoff counter value among $[0, w_0 - 1]$ slots and the backoff counter value decrements automatically at every slot until it becomes zero regardless of channel status, i.e., without performing CCA. In this way, the device can save power consumption for medium sensing, which is clearly different from the conventional CSMA/CA mechanism in IEEE 802.11 Wireless Local Area Networks (WLAN) [6].

Next, before attempting access to the wireless medium, the device performs carrier sensing (CCA) during two contention window slots. The CW starts from two and decreases by one at every idle contention window slot until it becomes zero. If either of two contention window slots is sensed busy, it immediately increases backoff stage k and resets CW to two. Then, it repeats the backoff count-down procedure with a new random backoff counter value among $[0, w_k - 1]$, and carrier sensing (up to two contention window slots) until the backoff stage $k = m$. If neither of two contention window slots for CCA is sensed busy at any backoff stage k, the device can have a chance to transmit the frame.

The transmitted frame can be considered as either success or failure (collision) depending on whether the ACK frame is successfully received or not within a specified time interval. In addition, if the channel is continuously sensed busy for five consecutive carrier sensing, the transmission also fails. Note that one carrier sensing corresponds to up to two contention window (CCA) slots after a random backoff duration. When the device fails transmission either due to five consecutive busy channel or due to a collision, the device is allowed to retransmit the frame up to three times. In that case, the

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[1] In order to achieve further battery life extension, another set of backoff exponents is defined as BE_k = 2, 3, 4, 5, and 5 for $0 \leq k \leq m$ [1].

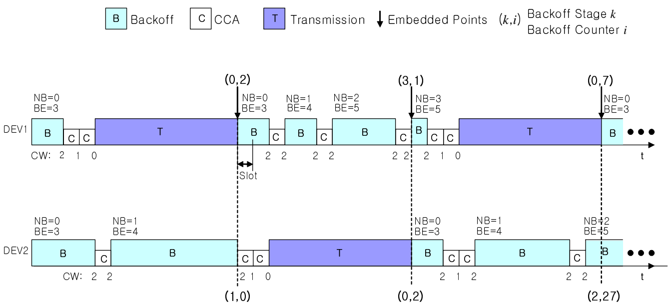

Fig. 1. An example of embedded points of the model.

retransmission phase starts with a random backoff counter value among $[0, w_k - 1]$ with backoff stage $k = 0$. After three retransmission failures, the frame is dropped eventually.

III. Modeling and Performance Evaluation of Slotted CSMA/CA

A. Markov Chain Model

Let's assume that n devices contend for transmission within one hop and that there is always a new frame available for transmission right after the successful transmission of a frame, which is a saturation condition. We further assume that superframes are fully dedicated to CAP only, and that backoff intervals, contention window slots and transmission boundaries are aligned by slot intervals without beacons in order to find performance limit of slotted CSMA/CA under pure CAP.

To build an embedded Markov chain [7], we consider embedded points to be right after the completion of a frame transmission of any device regardless of success or failure (see Fig. 1). Note that we observe a system right after transmissions, which is different from the conventional models for IEEE 802.11. Then, the random process of the backoff stage $S(t)$ and that of the backoff counter $C(t)$ constitute a two dimensional Markov chain $X(t) = \{(S(t), C(t))\}$. Let $b_{k,i}$ denote the steady state probability that a device is in backoff stage k and in backoff counter value i at embedded points. And let b_i and b_i^{cum} denote the probability that a device is in backoff counter value i and the cumulative probability that a device has a backoff counter value less than or equal to i, respectively. Then

$$b_i^{cum} = \sum_{j=0}^{i} b_j, \quad b_i = \sum_{k=0}^{m} b_{k,i} I(0 \le i \le w_k - 1), \tag{1}$$

where $0 \le i \le w_m - 1$ and $I(\cdot)$ denotes an indicator function. Let's define the probability that a tagged device completes transmission when its backoff counter value is i by τ_i^{tag}. Then

$$\tau_i^{tag} = (1 - b_{i-1}^{cum})^{n-1}, \quad 0 \le i \le w_m - 1, \tag{2}$$

since in order for a tagged device to win and transmit, the other $(n-1)$ devices should have backoff counter values greater than or equal to i. Next, the probability that a tagged device transmits is given by

$$\tau^{tag} = \sum_{k=0}^{m} \sum_{i=0}^{w_k - 1} \tau_i^{tag} b_{k,i}. \tag{3}$$

And the probability that a tagged device successfully transmits is given by

$$p_s^{tag} = \sum_{k=0}^{m} \sum_{i=0}^{w_k - 1} \tau_{i+1}^{tag} b_{k,i}. \tag{4}$$

Similarly, the probability that a tagged device at backoff stage k collides is given by

$$p_{c,k}^{tag} = \sum_{i=0}^{w_k - 1} (\tau_i^{tag} - \tau_{i+1}^{tag}) b_{k,i}, \quad 0 \le k \le m. \tag{5}$$

And the probability that a tagged device collides is found as

$$p_c^{tag} = \tau^{tag} - p_s^{tag} = \sum_{k=0}^{m} p_{c,k}^{tag}. \tag{6}$$

The probability of success $p_{s,(k,i)}^{other}$ by a device other than the tagged device, and the probability of collision $p_{c,(k,i)}^{other}$ by a device other than the tagged device, conditioned on backoff stage k and backoff counter i of the tagged device, can be derived as shown in (7) and (8) below and in (9) and (10) at the top of the next page.

$$p_{s,(k,i)}^{other} = \sum_{j=0}^{i-1} \binom{n-1}{1} b_j (1 - b_j^{cum})^{n-2}, \tag{7}$$

$$0 \le k \le m, 0 \le i \le w_k - 1 \tag{8}$$

Now, the balance equations at steady state are

$$b_{0,\alpha} = p_s^{tag} \frac{1}{w_0} + p_{c,m}^{tag} \frac{1}{w_0} + q_s^{(0,\alpha)} + q_c^{(0,\alpha)}, \quad 0 \le \alpha \le w_0 - 1, \tag{11}$$

$$b_{\gamma,\alpha} = p_{c,\gamma-1}^{tag} \frac{1}{w_\gamma} + q_s^{(\gamma,\alpha)} + q_c^{(\gamma,\alpha)}, \quad 1 \le \gamma \le m, 0 \le \alpha \le w_\gamma - 1, \tag{12}$$

where $q_s^{(\gamma,\alpha)}$ and $q_c^{(\gamma,\alpha)}$ denote the contributions to the steady state probability $b_{\gamma,\alpha}$ (backoff stage γ and backoff counter α) by the success and collision of devices other than the tagged device, respectively, and

$$q_s^{(\gamma,\alpha)} = \sum_{k=0}^{m} \sum_{i=0}^{w_k - 1} \left(p_{s,(k,i)}^{other} \times q_{(k,i,j)}^{(\gamma,\alpha)}(T_{succ}) \right) b_{k,i}$$

$$q_c^{(\gamma,\alpha)} = \sum_{k=0}^{m} \sum_{i=0}^{w_k - 1} \left(p_{c,(k,i)}^{other} \times q_{(k,i,j)}^{(\gamma,\alpha)}(T_{coll}) \right) b_{k,i}, \tag{13}$$

$$T_{succ} = \lceil (T_H + T_P + 2T_{prop} + t_{ack} + T_{ACK} + T_{LIFS}) / T_{slot} \rceil,$$

$$T_{coll} = \lceil (T_H + T_P + T_{prop} + T_{ACK\_TO}) / T_{slot} \rceil,$$

where T_{succ} and T_{coll} are the number of time slots for successful transmission and collision, respectively, and $\lceil x \rceil$ is the smallest integer which is greater than or equal to x. And T_H, T_P, T_{prop}, t_{ack}, T_{ACK_TO}, T_{ACK}, T_{LIFS}, and T_{slot} are the duration of a PHY and MAC header, the duration of a MAC payload, propagation delay, the waiting time until the ACK frame, ACK timeout interval, the duration of an ACK frame, long interframe space (LIFS), and the duration of a slot, respectively. Note that $x\%y$ denotes x modulo y.

$$q_{(k,i,j)}^{(\gamma,\alpha)}(T) = \begin{cases} 1, \quad \text{if } (i-(j+2+T)) = \alpha, k = \gamma \\ \sum_{h=0}^{T-1} \left(\prod_{u=k+1}^{k+1+h} \frac{1}{w_{(u\%(m+1))}} \right) \sum_{\ell_{k+1}} \cdots \sum_{\ell_{k+1+h}} I(k,i,j,h,\gamma,\alpha,T), \quad \text{otherwise,} \end{cases} \tag{9}$$

$$I(k,i,j,h,\gamma,\alpha,T) = \begin{cases} 1, \text{ if} \begin{cases} \{(i-j-1) + \sum_{d=k+1}^{k+h}(\ell_d+1) - T - 1 < 0, \\ \quad (i-j-1) + \sum_{d=k+1}^{k+1+h}(\ell_d+1) - T - 1 = \alpha, (k+1+h)\%(m+1) = \gamma, \\ \quad \text{and } (i-j) > 1 \; (\alpha \in [0, w_\gamma - 1], \ell_d \in [0, w_{(d\%(m+1))} - 1])\}, \\ \text{or } \{(i-j) + \sum_{d=k+1}^{k+h}(\ell_d+1) - T - 1 < 0, \\ \quad (i-j) + \sum_{d=k+1}^{k+1+h}(\ell_d+1) - T - 1 = \alpha, (k+1+h)\%(m+1) = \gamma, \\ \quad \text{and } (i-j) = 1 \; (\alpha \in [0, w_\gamma - 1], \ell_d \in [0, w_{(d\%(m+1))} - 1])\}, \end{cases} \\ 0, \text{ otherwise} \end{cases} \tag{10}$$

B. Analysis of Performance Limit

Let Ψ denote the random variable representing the number of backoff slots before a transmission. In order to have i backoff slots before transmission, at least one device should have the backoff counter value i while others have the values greater than or equal to i. So

$$P\{\Psi = i\} = (1 - b_{i-1}^{cum})^n - (1 - b_i^{cum})^n, \quad 0 \le i \le w_m - 1. \tag{14}$$

Then, the average number of idle (backoff) slots before transmission becomes

$$E[\Psi] = \sum_{i=0}^{w_m - 1} i \times P\{\Psi = i\}. \tag{15}$$

Finally, the throughput limit S becomes

$$S = \frac{np_s^{tag} \cdot (T_P / T_{slot})}{(E[\Psi] + 2) + np_s^{tag} \cdot T_{succ} + (1 - np_s^{tag}) \cdot T_{coll}}. \tag{16}$$

In order to find the performance limit of WPAN systems, we use the following values of the parameters: $T_{slot} = 320\mu$sec (20 symbols), $T_H = 480\mu$sec (15 bytes), $t_{ack} = 192\mu$sec (12 symbols), $T_{ACK_TO} = 864\mu$sec (54 symbols), $T_{ACK} = 352\mu$sec (11 bytes), and $T_{LIFS} = 640\mu$sec (40 symbols). For r = 250 Kbps, O-QPSK (4 bits/symbol) is used. Fig. 2 shows the saturation throughput. When the MAC payload size is 75, 50, and 25 bytes, and $n = 1$, the throughput limit with our analytical model is 101.35, 75.76, and 46.30 Kbps, respectively. In order to validate our model, we have conducted simulations. The event-driven simulation code was written in C. The results indicate that our analysis is closely matched with simulations. The throughputs are shown to be relatively low due to the short backoff windows and reduced CCAs for the sake of power saving compared to the conventional CSMA/CA in IEEE 802.11 WLAN.

IV. CONCLUSION

In this letter, we proposed a new analytical model for slotted CSMA/CA in IEEE 802.15.4 WPAN and evaluated its throughput limit. The relatively low throughput limit inherits from the fact that IEEE 802.15.4 mainly targets low power consumption for small WPAN devices rather than high throughput. The model can readily be utilized to evaluate performance of more energy-conserving slotted CSMA/CA with battery life extension.

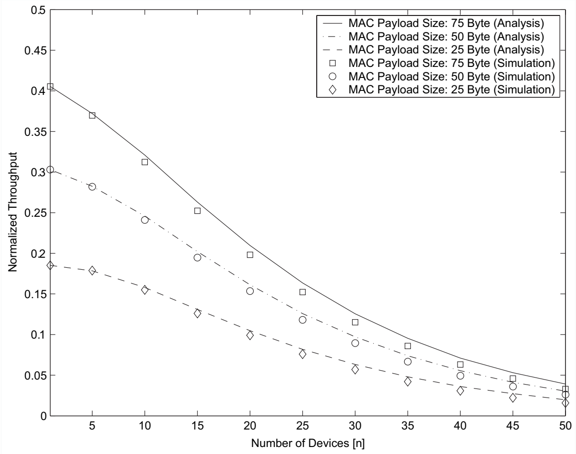

Fig. 2. Throughput limit of slotted CSMA/CA in IEEE 802.15.4 (no battery life extension).

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