Packet Loss Analysis of the IEEE 802.15.4 MAC without Acknowledgements

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***Abstract*— Transmission of the acknowledgement frame after a packet reception is optional in the IEEE 802.15.4 standard. Considering a set of sensor nodes, each of which has a packet to transmit at the beginning of an active period, we provide an analysis that yields the packet loss statistics of the non-acknowledgement mode of the standard. The analysis is based on a non-stationary Markov chain model and its accuracy is verified by ns-2 simulations.**

***Index Terms*— IEEE 802.15.4, medium access control (MAC), Markov chain, sensor networks, performance analysis.**

I. Introduction

The IEEE 802.15.4 standard [1] for low-rate low-power wirelss sensor networks (WSNs) has recently been ratified. It specifies a slotted carrier sense medium access with collision avoidance (CSMA-CA) mechanism for contention-based channel access, and a non-acknowledgement (NACK) mode for energy saving. The NACK mode is suitable for scenarios where sensors are redundantly deployed or where only a fraction of reports need to be collected [2]. It is important to understand the performance of packet delivery under these circumstances. In this letter, we develop an analytical model that yields accurate estimates of the average packet loss for the IEEE 802.15.4 medium access control (MAC) protocol under the NACK mode. Performance evaluations of the IEEE 802.15.4 MAC have so far mainly been simulation-based, but recently a few analytical studies have appeared. Leibnitz *et al.* [3] evaluated the energy consumption of the beacon-less mode of the standard via a non-stationary Markov chain model. Ramachandran *et al.* [4] performed an analysis of throughput and energy consumption for the NACK mode. A useful survey of other related work can be found in [4].

II. IEEE 802.15.4 CSMA-CA

We restrict our attention to beacon-enabled networks laid out in a star topology. Such a network operates with a superframe structure, which may consist of active and inactive portions. Let time be divided into consecutive time intervals called *beacon intervals* (BI). The active portion of a BI, called superframe duration (SD), may consist of a beacon frame, a contention access period (CAP) and a contention free period (CFP). In this work, we set the length of CFP to 0. The MAC attributes *macBeaconOrder* (BO) and *macSuperframeOrder* (SO) describe the lengths of BI and SD, respectively, where BO and SO are integers and $0 \leq SO \leq BO \leq 14$. More specifically, the lengths of BI and SD (measured in symbols) are given by *aBaseSlotDuration* $\times$ *aNumSuperframeSlots* $\times$ 2^{BO} and *aBaseSlotDuration* $\times$ *aNumSuperframeSlots* $\times$ 2^{SO}, respectively, where *aBaseSlotDuration* equals 60 symbols and *aNumSuperframeSlots* equals 16.

The time during a CAP is slotted and each slot is named *aUnitBackoffPeriod* which equals 20 symbols. A backlogged node starts with a backoff, the length of which (measured in slots) is uniformly chosen in the range of $[0, 2^{BE} - 1]$, where the integer-valued parameter BE represents the *backoff exponent* and takes an initial value given by *macMinBE*. At the end of the backoff period, the node performs clear channel assessment (CCA) to monitor the channel status. The node starts to transmit its packet if the channel is continuously sensed idle for $CW = 2$ times (where CW denotes the *contention window*). If the channel is detected to be busy, the node increases its BE by one (but no more than a pre-assigned value called *aMaxBE*) and performs another random backoff. The packet is discarded after a maximum number of attempts, *macMaxCSMABackoffs*, is reached.

In this work, we set $CW = 1$ to simplify the analysis. Note that in [4], it is shown that setting $CW = 1$ improves both throughput and energy efficiency in the NACK mode.

III. Packet Loss Analysis

A scenario where many stations attempt to transmit packets simultaneously is problematic for CSMA [5], as the collision rate will be high. However, this is precisely the type of workload anticipated for many WSN applications [2]. Consider, for example, a real-time temperature monitoring network of C nodes using the NACK mode of the IEEE 802.15.4 MAC. Each node sends a message of length L slots in every BI to its cluster head. Out-of-date packets, which fail to be transmitted by the end of the current BI will be discarded. In the following, we present our analytical model that yields the distribution of the number of successful transmissions out of C nodes, from which the loss statistics per BI cycle are derived.

A. Attempt probability

The attempt probability has been successfully used to analyze the truncated binary exponential backoff algorithm in

Manuscript received August 16, 2006. The associate editor coordinating the review of this letter and approving it for publication was Prof. Nasir Ghani. This work was supported by the National ICT Australia (NICTA) and the Australian Research Council (ARC).

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Digital Object Identifier 10.1109/LCOMM.2007.061295.

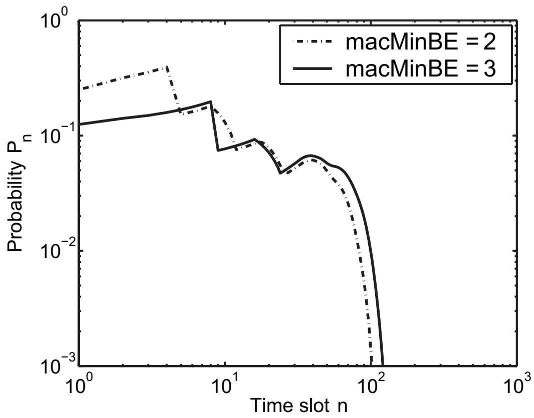

Fig. 1. Attempt probability.

Ethernet [6]. The same technique was extended to the IEEE 802.11 distributed coordination function in [5]. According to the description in Section I, the probability P_n that an IEEE 802.15.4 node senses or makes an attempt for the channel in a particular slot n can be approximated by:

$$P_n = \sum_{m=0}^{M} P_n(m), \ n = 0, 1, 2, \ldots \tag{1}$$

where $P_n(m)$ denotes the attempt probability that a node chooses slot n for its mth attempt and M equals *macMaxCSMABackoffs*. $P_n(m)$ is determined using the following recursive equations:

$$P_n(0) = \begin{cases} \frac{1}{W_{min}} & , 0 \le n < W_{min}. \\ 0 & , \text{otherwise.} \end{cases}$$

$$P_n(m) = \frac{1}{W} \sum_{k=\max(0,n-W+1)}^{n} P_k(m-1), \quad m > 0, \tag{2}$$

where $W_{min} = 2^{macMinBE}$, and $W = min(2^m W_{min}, 2^{aMaxBE})$. Fig. 1 shows P_n for $aMaxBE = 5$, and, alternately, $macMinBE = 2$ and $macMinBE = 3$. The same result can be obtained using a convolution method [3], which is equivalent to (2). The distinctive saw tooth pattern in Fig. 1 is consistent with the results in [3], [5], [6].

B. Non-stationary Markov Chain

The nodes are classified into active nodes or inactive nodes. The former includes backoff nodes which are in the backoff state and transmitting nodes which are transmitting their packets. The latter includes: 1) successful nodes, which have successfully completed their transmissions without collision; 2) collided nodes, which simultaneously detected an idle channel and started transmitting at the same slot (as a result their packets collided); 3) aborted nodes, which have discarded their packets after exceeding the *macMaxCSMABackoffs* attempts or could not finish transmission in the current CAP. The packet loss can be caused by either collision or abortion.

Consider the following non-stationary 3-D Markov chain denoted $\psi_n(c, r, u)$, where c is the number of backoff nodes, r describes the number of slots that have been used for the ongoing transmission or transmissions if multiple nodes transmit from the same slot (i.e., in the case of collision), and u the number of nodes which have successfully obtained the channel (with no collision). Assuming perfect CCA operations, let us divide the state space into:
1) contention states, in which the channel is clear ($r = 0$). If backoff nodes attempt, they detect the clear channel and start transmission in the next slot since $CW = 1$. Note that contention states with $c = 0$ are absorbing states;
2) transmission states, in which some node(s) are transmitting ($r \neq 0$), and if backoff nodes attempt, they find the channel busy and then perform another random backoff until *macMaxCSMABackoffs* is reached.

For contention states, the time-varying transition probabilities are given by the following binomial form:

$$s_c^k(n) = \binom{c}{k} P_n^k (1 - P_n)^{c-k}, \qquad k = 0, 1, ..., c. \tag{3}$$

where we define $s_0^0 = 1$. When $k = 1$, one node attempts the channel and starts transmission in the next slot, and the next state at $n + 1$ becomes $\psi_{n+1}(c - 1, 1, u + 1)$. When $2 \le k \le c$, multiple nodes attempt in the same slot and they simultaneously find the channel clear and start transmission, and the next state is $\psi_{n+1}(c - k, 1, u)$. When $k = 0$, no node attempts and the next state variables remain unchanged. Similarly, for transmission states, the time-varying transition probabilities are given by:

$$g_c^k(n) = \binom{c}{k} P_n(M)^k (1 - P_n(M))^{c-k}, \ k = 0, 1, ..., c, \tag{4}$$

where $P_n(M)$ is defined in (2) when $m = M$, and we define $g_0^0 = 1$. If a node performs its last (i.e., Mth) attempt in transmission states, it detects the channel busy and then it aborts. Therefore, if $1 \le k \le c$, these k nodes abort and the next state becomes $\psi_{n+1}(c - k, r', u)$, where $r' = \bmod (r + 1, L + 1)$, meaning that r increases by one and returns to 0 when it reaches L (i.e., the packet(s) have finished transmission). In particular, when $k = 0$, no node performs its last attempt, and the next state is $\psi_{n+1}(c, r', u)$.

The state space with transitions is shown in Fig. 2. Let us define the state vector at time slot n as

$$\Psi_n = \{\psi_n(C, 0, 0), \psi_n(0, 1, 0), \ldots, \psi_n(0, 0, 0), \psi_n(1, 1, 0), \\ \ldots, \psi_n(C - 1, 1, 1), \psi_n(C - 2, 2, 1), \ldots, \psi_n(0, 0, C)\}.$$

The initial Ψ_0 is given by $\{1, 0, 0, \ldots, 0\}$, since all C nodes commence at the beginning of a CAP period. Thus, the time-varying transition matrix T_n can be obtained using (3) and (4). The following simple power method is then applied,

$$\Psi_{n+1} = \Psi_n T_n.$$

Let X_n be a random variable representing the number of successfully transmitted nodes at time slot n. The average packet loss δ_n is given by:

$$\delta_n = \sum_{x=0}^{C} (C - x) \ p(X_n = x),$$

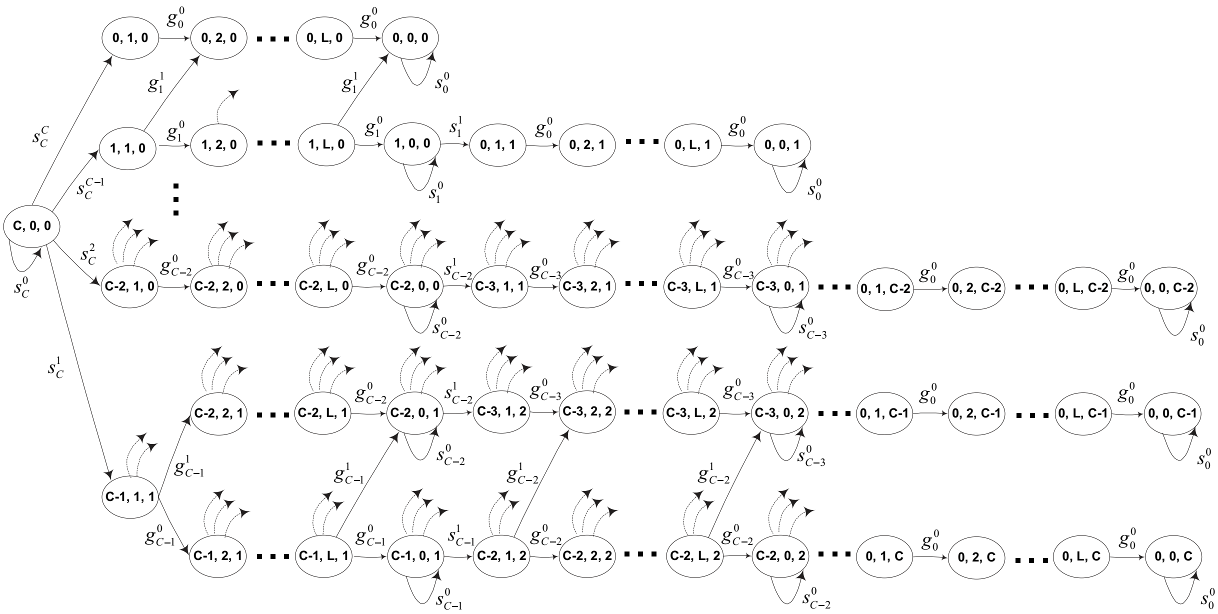

Fig. 2. Markov chain model. Note that s_c^k and g_c^k represent $s_c^k(n)$ and $g_c^k(n)$, respectively.

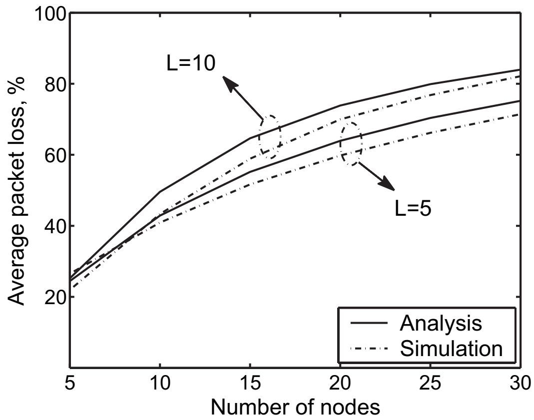

Fig. 3. Average packet loss when $SO = 2$.

where $p(.)$ denotes the probability mass function,

$$p(X_n = x) = \sum_{c=0}^{C} \psi_n(c, 0, x) + \sum_{c=0}^{C} \sum_{r=1}^{L} \psi_n(c, r, x+1),$$

where the second term represents the case that the last node successfully obtains the channel but is still in transmission. The average packet loss percentage is given by $\frac{\delta_n}{C} \times 100$.

IV. Numerical Evaluation and Discussion

To verify the accuracy of the proposed model, we compared the analytical results with simulation. The simulation results, averaged over 1000 independent simulation runs, were obtained using the IEEE 802.15.4 MAC implementation in the ns-2 simulator [7] (v2.28), together with the patches developed especially for the NACK mode by the authors of [4]. We used all the default parameter values (e.g., $macMinBE = 3$, $aMaxBE = 5$, $M = 5$), except that for CW we used 1 instead of 2. The 2.4 GHz frequency band of the standard was used [1], and thus one *aUnitBackoffPeriod* equals 10 bytes.

Our analytical model is able to closely predict the average packet loss. For the cases $SO = 0$ and 1, the analysis and simulation curves were closely matched and at times crossed each other. In contrast, for $SO = 2$, the analysis curve was consistently higher than the simulation one. This is because the attempt probabilities become extremely small when the time approaches the end of the last attempt (as shown in Fig. 1), which results in a lower number of successful transmissions in the analysis (and thus more losses). For brevity, we present here only the result for $SO = 2$ in Fig. 3. It shows that the packet loss in the NACK mode is considerable and also demonstrates that the cluster size and message length have a significant influence. In general, a network with more nodes and longer message length suffers more packet losses.

V. Conclusion

We have developed an analytical model that yields the average packet loss in the IEEE 802.15.4 MAC under the NACK mode. The accuracy of the model has been verified by ns-2 simulations. We discovered that the packet loss in such networks can be extremely high. Our results suggest that the cluster size and message length need to be carefully chosen for satisfactory performance.

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