Analytical Model of Single-hop IEEE 802.15.4 Data Aggregation in Wireless Sensor Networks

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Abstract— **This paper introduces a new 4D Markov chain model for IEEE 802.15.4 wireless transmission, which corrects errors in an existing 3D model and provides more accurate results. It also introduces an analytical technique for calculating the pdf and mean of the number of time slots required to complete all transmissions, when a set of nodes contend for the channel at the beginning of a superframe. It is assumed that transmission takes place in beacon mode but without acknowledgement (NACK mode). The model can determine the optimum value of the MAC attribute SO required to save energy, and the shortest delay required to receive all transmitted packets with an acceptable probability. This model also suggests an upper threshold for the number of nodes, and the packet length required, to achieve acceptable end-to-end delay. A traffic model for the aggregated data generated by the coordinating node may also be derived based upon this analysis.**

Keywords- 802.15.4 beacon enabled mode, Markov chain, analytical modeling, traffic model analysis

I. BACKGROUND AND MOTIVATION

Wireless sensor networks have many applications such as environmental monitoring, conferencing, disaster relief, rescue operations, and police operations. Such a sensor network must be able to sense the required physical quantity over the entire area to be monitored. Because adjacent sensor nodes may collect similar data, it is generally assumed that the sensing data is highly redundant in densely deployed sensor networks. Therefore data loss due to radio transmission is assumed to have no effect on sensing integrity or accuracy, and acknowledgement messages to confirm that data has been received are unnecessary; indeed they are not implemented in order to save power [1]. Also, data aggregation is possible to reduce the overall number of packets transmitted in such cases. For example, in applications to monitor or trace a specific event such as the motion of an object, only those nodes adjacent to the event produce data from their sensors, and a cluster head (a Full Function Device or FFD in IEEE 802.15.4) can collect all the sensing data from its neighbors then aggregate the data into one packet to describe the sensed event.

This assumption is not always valid in low-density sensor networks or sensor networks without data redundancy. Indeed, a distributed coordinate-free algorithm has been proposed in order to save power [2]-[4], which elects only those active nodes necessary for full sensing coverage – redundancy in the sensing data is then virtually eliminated, and each packet containing sensed data must be received reliably, with minimal packet loss. However, such cases are not discussed in this paper.

A. Assumptions

In this paper it is assumed that the IEEE 802.15.4 MAC protocol is used with beacon mode (slotted CSMA/CA) and without acknowledgement (NACK mode) in a wireless sensor network. Each active sensor node is a slave node which sends data to the same next hop node S. S is a Full Function Device (FFD) which generates MAC superframes, and transmits a beacon message at the beginning of each one. After S receives all the packets from its neighboring slave nodes, it then aggregates the data to generate a single packet, and sends it to the base station directly or via other intermediate FFD nodes.

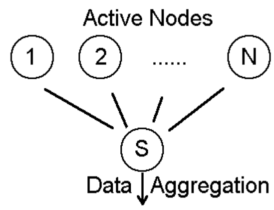

Fig. 1. Single hop *N*-to-one model.

This paper focuses on modeling and analysis of traffic in a sensor network with such an *N*-to-one data aggregation model (Fig. 1), where each of the *N* active nodes generates a packet during each IEEE 802.15.4 superframe, and only one packet needs to be sent during the superframe. This is called *batched arrivals* [5], where many nodes attempt to transmit packets at the same time, possibly resulting in severe collisions [6]. This type of data traffic appears in many sensor network applications [7]-[9]; it is called *one-shot data* (OSD) in [10]. For example, in many sensor network applications to monitor the environment, such as a bush fire detection system or a humidity monitoring system, when the temperature rises and exceeds a threshold near the fire itself, or humidity rises before rainfall, nearby nodes will be triggered and will simultaneously send one packet each.

In 802.15.4, assume all the *N* nodes each attempt to send their packet to S after receiving a beacon message at the beginning of the superframe. At the end of the CAP

(Contention Access Period), S will aggregate all the received packets into one packet and forward it to the base station after the superframe is complete. Each of the *N* nodes prepares a packet containing its sent data, in time for each new superframe, to be sent during the CAP. If such a packet cannot be sent due to contention, it will be discarded without being transmitted.

The traffic model determines the expected number of timeslots taken for all *N* packets either to finish their transmissions (either successfully or with a collision) or to discard their packets. The model also determines the probability mass function describing the probability that all *N* nodes complete their transmission by a specific timeslot, *n*. Hence the length of Contention Access Period in IEEE 802.15.4 required to ensure acceptable packet loss can be derived. Based on this model, if the number of active nodes *K* ($\leq N$) is random, following a given distribution (because in many applications, not every node always has data to send for every superframe duration), the probability of all active nodes finishing their transmission during a CAP can also be calculated accordingly.

B. Characteristics and parameters of the IEEE 802.15.4 MAC protocol with beacon mode

The IEEE 802.15.4 standard specifies a MAC protocol that includes a duty cycling operation, where nodes are allowed to stay in sleep state for most of the time to save energy, and it also specifies a CSMA/CA mechanism for contention-based channel access. It can operate in beacon-enabled or non-beacon-enabled modes. In beacon-enabled mode, a beacon frame is broadcasted by the network coordinator in order to implement network synchronization. In the non-beacon-enabled mode, there is no beacon frame and operation is asynchronous. Slotted CSMA/CA is used in beacon-enabled networks, where beacon messages are periodically sent by the network coordinator to its associated nodes.

In this paper, it is assumed that beacon-enabled mode is used in a single-hop star topology. Such a network operates with a superframe structure, which may consist of active and inactive portions. Time is divided into consecutive time intervals called beacon intervals (BI). At the beginning of a BI, the nodes simultaneously wake up and the coordinator broadcasts a message called the beacon frame (BF) which also specifies the next wake-up time. The superframe duration (SD) denotes the active portion of the superframe, which may consist of a BF, a contention access period (CAP) and a contention free period (CFP). Assume that the CFP is set to zero so that slave nodes are only permitted to operate in contention-based access mode during the CAP.

The MAC attributes macBeaconOrder (BO) and macSuperframeOrder (SO) denote the lengths of the BI and SD, respectively, where BO and SO are integers and $0 \leq \text{SO} \leq \text{BO} \leq 14$.

$\text{SD} = \text{aBaseSlotDuration} \times \text{aNumSuperframeSlots} \times 2^{\text{SO}}$, where aBaseSlotDuration is equal to 60 symbols and aNumSuperframeSlots is equal to 16.

The time during a CAP is slotted, and each slot is of duration aUnitBackoffPeriod (= 20 symbols), which is the smallest time unit in a superframe. A slave node starts with a random backoff, the length of which (measured in slots) is uniformly chosen in the range $[0, 2^{\text{BE}} - 1]$. BE represents the backoff exponent and takes an initial value given by macMinBE. macMinBE can be set to a value between 3 and 8, and is set to 5 by default [11]. macMaxCSMABackoffs (range: 0–5, Default = 4) is the maximum number of backoffs each node will attempt before declaring a channel access failure and discarding the packet.

In this paper, it is assumed that each node consists of a wireless radio transmitter (**tx**) and receiver (**rx**) compliant with the IEEE 802.15.4 specification, operating in the 2.4 GHz frequency band with a data rate of 250 kb/s (sample rate: 62.5 kb/s). Therefore each slot (aUnitBackoffPeriod = 20 symbols) can transmit 10 bytes (80 bits). The data packet length is between 9 and 127 bytes, where 127 is the maximum length of a PHY packet (aMaxPHYPacketSize). Therefore the packet length may vary between 1 and 13 slots.

The channel-sensing mechanism ensures that the channel is clear of activity for the duration of a contention window (CW). The 802.15.4 standard defines the CW duration to be 2 backoff slots in order to avoid a data packet colliding with an ACK message in ACK mode. At the end of the backoff period, the node performs a clear channel assessment (CCA) to monitor the channel status. If the channel is idle, it performs another CCA on the boundary of the next backoff slot before sending a packet.

In the IEEE 802.15.4 standard, it is optional for a receiver to transmit an acknowledgment after it receives a packet (ACK mode). In this paper, it is assumed that acknowledgements are turned off, i.e. in non-acknowledgment (NACK) mode, to save energy, and CW is set to 1 in order to simplify the analysis. For NACK mode, setting CW to 2 is unnecessary [12]. Setting CW to 1 in NACK mode also improves the transmission efficiency [1].

II. MARKOV CHAIN MODEL

The traffic model analysis in this paper is based on an existing 3D Markov chain model [13]. The non-stationary 3D Markov chain is denoted by $\psi_n(c, r, u)$, where c is the number of backoff nodes at timeslot n; r ($1 \leq r \leq L$) is the number of slots after one or more nodes start transmission where L is the packet length; u is the number of nodes which have finished transmission successfully or are transmitting without collision.

The nodes are classified into active nodes or inactive nodes. Active nodes include backoff nodes which are in the backoff state, and transmitting nodes which are transmitting their packets. Inactive nodes include:

1. *successful nodes*, which have successfully completed their transmissions without collision;
2. *collided nodes,* which simultaneously detected an idle channel and started transmitting during the same slot (hence their packets collided with one another); aborted nodes, which have discarded their packets after exceeding

macMaxCSMABackoffs attempts or could not finish transmission in the current CAP.
3. *aborted nodes*, which have discarded their packets after exceeding macMaxCSMABackoffs attempts or could not finish transmission in the current CAP.

The state space for the 3D Markov chain model [13] is divided into:
1. *contention states*, in which the channel is clear ($r = 0$). If backoff nodes attempt transmission, they detect a clear channel and start transmission in the next slot because CW = 1. 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 to transmit, they find that the channel is busy and then perform another random backoff until macMaxCSMABackoffs is reached.

A. Correction to the existing 3D Markov chain model

In the original 3D Markov chain model [13], the time-varying transition probability for contention states when the channel is clear ($r = 0$) is:

$$\psi_n(c,0,u) \xrightarrow{s_c^k(n)} \psi_{n+1}(c-k,0,u) \text{ for } k=0$$

$$\psi_n(c,0,u) \xrightarrow{s_c^k(n)} \psi_{n+1}(c-k,1,u) \text{ for } k>1$$

$$\psi_n(c,0,u) \xrightarrow{s_c^k(n)} \psi_{n+1}(c-k,1,u+1) \text{ for } k=1$$

where

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

Therefore $s_c^k(n) = (1-P_n)^c$ for $k = 0$, which is a constant. Hence for $k = 0$ when $n \to \infty$, $\psi_n(c,0,u) \xrightarrow{(1-P_n)^c} \psi_{n+1}(c,0,u)$. This is not correct, because during slot n (with $P_n = 0$), no node can be carrying out backoff, and each node should either be transmitting or have finished/abandoned its transmission. (For the definition of P_n, refer to (5) in the Appendix). Another example of this error relates to state vector element $\psi_{2^{macMinBE}-1}(C,0,0)$; it is impossible that all C nodes have not attempted their first backoff by 2^{macMinBE} slots and stay in state $\psi_{2^{macMinBE}-1}(C,0,0)$ with non-zero probability.

To correct this error, the time-varying transition probability for contention states $\psi_n(c,0,u)$ when the channel is clear should be recalculated, so that not only should the probability P_n that a node makes an attempt to sense the channel at slot n be considered, but also the probability $P_c^k(t)$ should be considered that k of the c nodes start sending at slot t. t is the number of slots after the end of the last transmission.

To solve this problem, a 4D Markov chain model is proposed in this paper, where the 3D state vector element $\psi_n(c,r,u)$ is transformed into $\psi_n(c,r,t,u)$. The 4D time-varying transition probability for contention states $\psi_n(c,0,u)$ is corrected as follows:

$$\psi_n(c,0,t,u) \xrightarrow{f_c^k(n,t)} \psi_{n+1}(c,0,\text{mod}(t+1,2^{BE}),u) \text{ for } k=0$$

$$\psi_n(c,0,t,u) \xrightarrow{f_c^k(n,t)} \psi_{n+1}(c-k,1,\text{mod}(t+1,2^{BE}),u) \text{ for } k>1$$

$$\psi_n(c,0,t,u) \xrightarrow{f_c^k(n,t)} \psi_{n+1}(c-k,1,\text{mod}(t+1,2^{BE}),u+1) \text{ for } k=1$$

$$\psi_n(0,0,0,u) \xrightarrow{f_c^k(n,t)} \psi_{n+1}(0,0,0,u) \text{ for } c=0$$

$$\begin{aligned} f_c^k(n,t) &= s_c^k(n) + s_c^0(n) \cdot P_c^k(t) \text{ for } k > 0. \\ &= s_c^k(n) + (1-P_n)^c \cdot P_c^k(t) \\ f_c^k(n,t) &= s_c^0(n) \cdot P_c^k(t) \text{ for } k = 0 \\ &= (1-P_n)^c \cdot P_c^k(t) \\ f_c^k(n,t) &= 0 \text{ for } k < c \text{ and } n > MaxN \\ f_c^k(n,t) &= 1 \text{ for } k = c \text{ and } n > MaxN \end{aligned} \qquad (2)$$

The conditional probability that k ($0 \le k \le c$) nodes start sending at slot t is $P_N^k(t)$, given that no node starts sending before slot t.

$$P_c^k(t) = \binom{k}{c}\left(\frac{1}{\min(2^{BE}-t, MaxN-n)+1}\right)^k \left(\frac{\min(2^{BE}-t, MaxN-n)}{\min(2^{BE}-t, MaxN-n)+1}\right)^{c-k} \qquad (3)$$

To simplify the calculation, BE = macMinBE for $\psi_n(C,0,t,0)$, and BE = macMaxBE for any $\psi_n(c,0,t,0)$ with $c < C$. $\min(2^{BE} - t, MaxN - n) + 1$ is the number of slots possible before a node's backoff period expires.

If $n = MaxN$, all nodes have completed their backoff, and no non-zero number of nodes ($c - k$) will attempt to sense the channel later ($n > MaxN$). $MaxN$ is the highest numbered slot with $P_n(n) > 0$.

The time-varying transition probability for transmission states $\psi_n(c,r,u)$ is unchanged, where $r > 0$.

3D model:

$$\psi_n(c,r,u) \xrightarrow{g_c^k(n)} \psi_{n+1}(c, r' = \text{mod}(r+1, L+1), u)$$

4D model:

$$\psi_n(c,r,0,u) \xrightarrow{g_c^k(n)} \psi_{n+1}(c, r' = \text{mod}(r+1, L+1), 0, u)$$

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

For the definition of $P_n(M)$, refer to (6) in the Appendix. Therefore the state vector at timeslot n is:

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

The initial Ψ_0 is given by $\{1, 0, 0, \ldots, 0\}$, because all C nodes are contending for the channel at the beginning of a CAP period. Thus, the time-varying transition matrix T_n can be obtained using (2) and (4). Furthermore, the following time-varying transition process is applied:

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

Using the 4D Markov chain model, the probability $P_n(finished)$ that all the C nodes have finished their transmission by timeslot n, can be derived. Each of the C nodes may have finished its transmission either successfully or with a collision, or may have discarded its packet because the number of attempts required to sense whether the channel is busy was larger than MacMaxbackoff.

$$P_n(finished) = \sum_{u=0}^{C} \psi_n(0,0,0,u) \cdot 1 + \sum_{c=0}^{C-u} \sum_{u=0}^{C} \psi_n(c,L,0,u) \cdot g_c^c(n)$$
$$= \sum_{u=0}^{C} \psi_{n+1}(0,0,0,u)$$

$P_n(finished)$ in the formula above is equal to the sum of two probabilities:

- The first term is the probability that the channel is clear during timeslot n and that all nodes have completed transmission.
- The second term is the probability that no nodes are carrying out backoff during timeslot $n + 1$ and that all transmissions have been successful. In other words, this is the probability that the last transmission ended at timeslot n while all the remaining contending nodes were attempting their last try and discarding their packets (the second term).

However, the second term can be omitted in the calculation, because they should all transit to $\psi_{n+1}(0,0,0,u)$ at the next time slot $n + 1$.

Then the probability mass function for all transmissions finishing exactly at timeslot n can now be derived:

$$P_n(finishing) = 0 \qquad \text{for } n < L$$
$$P_n(finishing) = P_n(finished) - P_{n-1}(finished)$$
$$= \sum_{u=0}^{C} \psi_{n+1}(0,0,0,u) - \sum_{u=0}^{C} \psi_n(0,0,0,u) \qquad \text{for } n \geq L$$

$E(finishing)$ is the expected (mean) transmission time for all C nodes to finish transmission, assuming a uniform packet length of L.

$$E(finishiing) = \sum_{n=0}^{\infty} n \cdot P_n(finishing)$$

B. Calculation and simulation results

Fig. 2 shows the probability distribution for $P_{finishing}(n)$, which is the probability that the transmission finishes at slot n. The integral of this probability is unity in the 4D Markov chain model, as expected. However this integral is only 0.906 when calculated by the 3D model [13], which means for n > MaxN + L, there is a probability of 1 – 0.906 of finishing the transmission, whereas this probability should be zero according to the definition of MaxN. For more nodes C, the integral of $P_{finishing}(n)$ decreases even further until it approaches zero using the 3D model. However for the 4D model, the integral of $P_{finishing}(n)$ is always equal to unity as shown in Fig. 3, despite the increase in C or L.

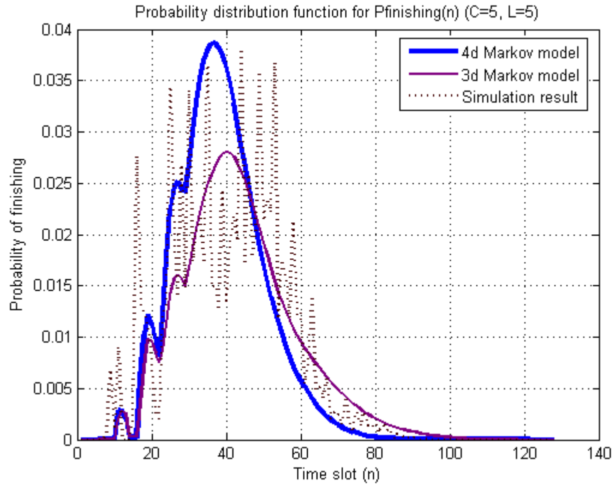

Fig. 2. Comparison between 3D and 4D models, and simulation.

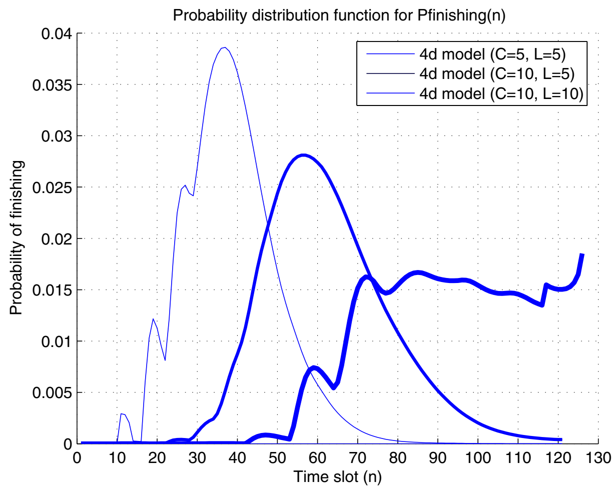

Fig. 3. Probability distribution for transmission finishing at slot n.

Fig. 2 also shows the simulation result obtained using OPNET simulator Version 11.5, and the open source toolset for 802.15.4 with beacon enabled mode (Version 2.0) provided by open-ZB [15]. Also, the original source code [15] with contention window (CW) = 2 has been revised to $CW = 1$ in this paper. The result with 10,000 simulations is more bursty than the results from the 3D and 4D models, however the peak value obtained in the simulation is closer to the 4D model than to the 3D model.

Fig. 3 also shows that, for a larger number of nodes (C = 10) and a longer packet length (L = 10), the probability of finishing increases instead of approaching zero when the time slot (n) approaches the end (slot MaxN + L). This means that it is likely that some nodes cannot finish their transmission at their final attempt and must abandon their packets.

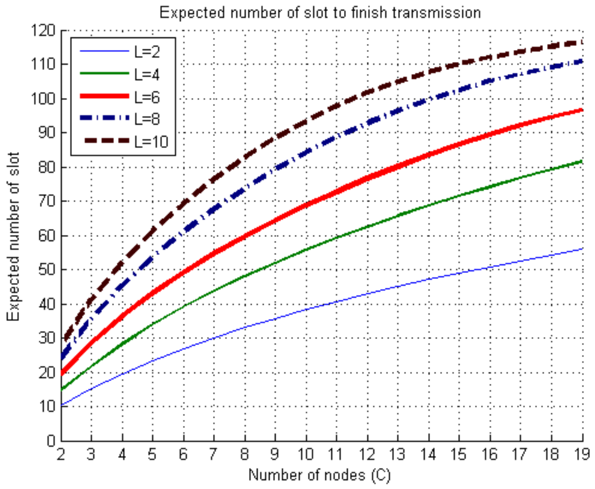

Fig. 4. Expected number of time slots required to finish transmission.

Fig. 4 shows the expected number (mean) of time slots E(finishing) for different numbers of nodes C, and different packet lengths L. It apparently increases when the number of nodes or the packet length increases.

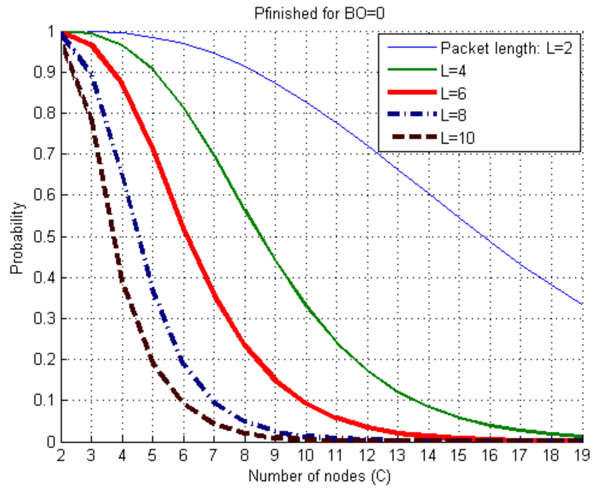

Fig. 5. Probability of finishing transmission for SO = 0.

Fig. 5 and Fig. 6 show the probability $P_n(finished)$ that transmission is complete at the end of a superframe with SO = 0 and SO = 1 respectively; when number of nodes or packet length increases, the probability $P_n(finished)$ decreases. Fig. 5 shows for more than three nodes (C > 3), the probability of finishing transmission at the end of 48 slots for BO = 0 decreases dramatically for packet length $L \geq 8$. However in Fig. 6, $P_n(finished)$ decreases more slowly for $C < 8$ and $L \geq 8$, and for L = 2, $P_n(finished)$ is always larger than 98% for C ≤ 19. For SO ≥ 2, $P_n(finished)=1$ because the number of slots in the superframe is larger than MaxN + L. From these graphs, users can determine the optimum value of SO for saving energy and the shortest duration required for receiving all packets with an acceptable probability. For example, Fig. 6 shows that, for $C < 10$ and $L = 4$, and for $C < 8$ and $L = 6$, the probability of finishing transmission with SO = 1 is more than 99%, in such cases the optimum value SO = 1 is selected to avoid longer data aggregation delay, and to avoid wasting energy with larger SO.

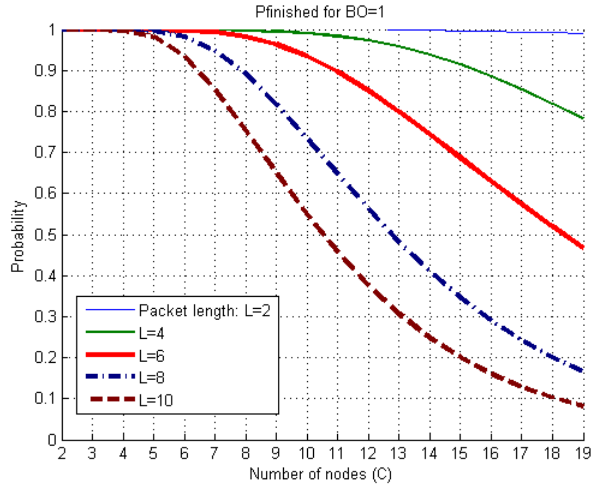

Fig. 6. Probability of finishing transmission for SO = 1.

Furthermore, an analytical model for the aggregated data traffic generated by the coordination node S after receiving all packets from adjacent slave nodes may consequently be derived. Once the optimum value of SO is selected, the data aggregation delay on coordination node S can be calculated, which is equal to the superframe duration (SD), or the contention access period (CAP) assuming the contention free period (CFP) is zero. After a superframe duration (SD), coordination node S can aggregate all received packets during the last SD to generate an aggregated packet, and forward it to the base station directly or via other intermediate nodes.

SD = aBaseSlotDuration × aNumSuperframeSlots × 2^{SO} (aBaseSlotDuration = 60 symbols; aNumSuperframeSlots = 16).

III. Conclusions

This paper introduced a revised and corrected 4D Markov chain model to calculate both the probability distribution function and mean number of time slots required to finish all transmissions, when C nodes contend for the channel at the beginning of a superframe and each transmits a packet of length L using beacon mode in the IEEE 802.15.4 standard without acknowledgement (NACK mode). This 4D model is developed from an existing 3D Markov chain model [13], rectifying errors, and providing a more accurate result.

This model can be used to decide the optimum value of SO to save energy, and provide the shortest delay which permits all packets to be received with an acceptable probability. Furthermore, an analytical model for the aggregated data traffic generated by the coordination node after receiving all packets from adjacent slave nodes may be derived from this model.

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Appendix : Attempt Probability

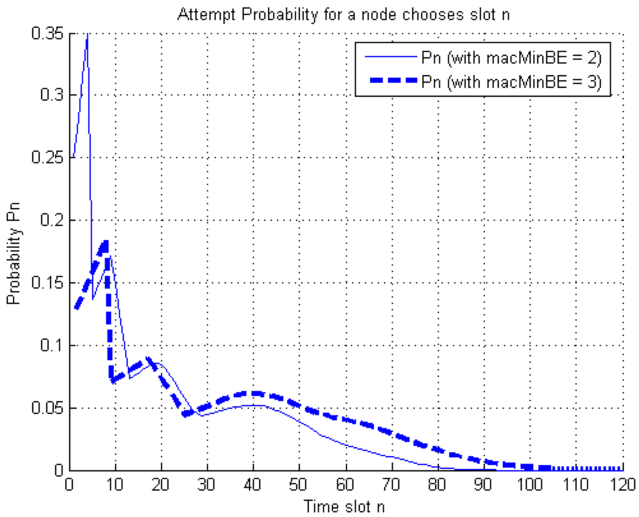

Fig. 7. Attempt probability P_n

The attempt probability has been successfully used to analyze the truncated binary exponential backoff algorithm in both Ethernet [14] and in the IEEE 802.11 Distributed Coordination Function. Here, this is the probability that an IEEE 802.15.4 node senses the channel or makes an attempt to access it in a particular slot n, and can be approximated by [13]:

$$P_n = \sum_{m=0}^{M} P_n(m), \quad n = 0, 1, 2... \tag{5}$$

where $P_n(m)$ denotes the attempt probability that a node chooses slot n for its mth attempt and M is equal to *macMaxCSMABackoffs*.

$$P_n(0) = \frac{1}{W_{\min}}, \quad 0 \le n < W_{\min}$$

$$P_n(0) = 0 \text{ otherwise}$$

$$P_n(m) = \frac{1}{W} \sum_{k=\max(0,n-W)}^{n-1} P_k(m-1), \quad m > 0 \tag{6}$$

where $W_{min} = 2^{macMinBE}$, and $W = min(2^m W_{min}, 2^{macMaxBE})$.

Figure 7 shows P_n for *macMinBE* = 2 and *macMinBE* = 3 with *macMaxBE* = 5. Figure 8 shows $P_n(m)$ and P_n for *macMinBE* = 3 with *macMaxBE* = 5.

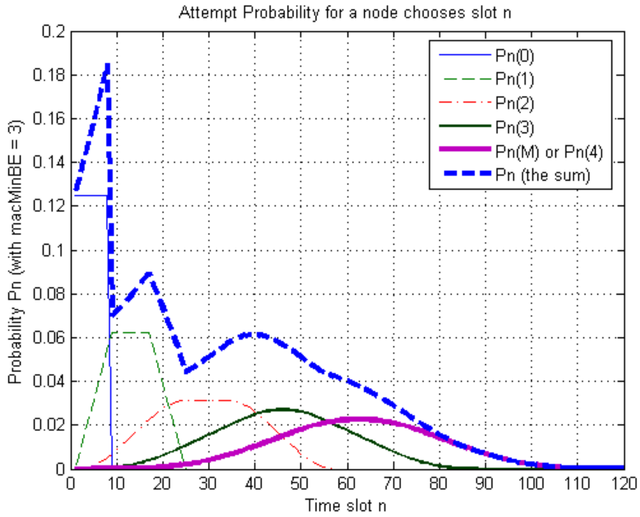

Fig. 8. Attempt probability $P_n(m)$.

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