Performance Evaluation of Data Delivery Procedure in IEEE 802.15.4 Based on Discrete-Time Markov-Chain

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***Abstract*—Data delivery procedure (DDP) based on IEEE 802.15.4 involves a series of sub-procedures. They are CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance), data transmission (Tx), acknowledgment (ACK) related behavior (ACK wait duration and ACK transmission). Any failure during this procedure leads to an unsuccessful delivery. This procedure, in fact, determines the network performance, yet not received adequate concern. The algorithm of CSMA/CA, which generally has also been simplified in previous literature. We investigate a discrete-time Markov-chain (DTMC) for DDP without simplification. Due to these sub-procedures, four cases during this procedure are proposed via DTMC models. Particularly, we evaluate the impact of different times of retransmission (ReTx) on the network performance. The performance is investigated in terms of throughput, data delivery ratio and time delay. We also verify our analysis via simulation. Both theoretical and simulation imply that less ReTx can bring better performance.**

Keywords-802.15.4 MAC; CSMA/CA; Data delivery procedure; Discrete-time Markov-Chain; Performance evaluation.

I. INTRODUCTION

Since IEEE 802.15.4 [1] was firstly introduced ten years ago, it has distinguished itself for low data-rate, low cost and low energy consumption. Both academia and industry have devoted great effort to this field.

We note that recent literature has addressed more on some specific IEEE 802.15.4 protocol improvement and applications than the comprehensive performance study itself. Meanwhile, when 802.15.4 MAC performance is concerned, much attention has been focused on CSMA/CA algorithm only, which generally has also been simplified. However, this algorithm is just the beginning of DDP, followed by data Tx, ACK wait duration, and ACK Tx. In this paper, we illustrate a convincing analysis via comprehensive DDP, with unsimplified CSMA/CA. Our work is to evaluate the MAC performance during the procedure of delivering packets between two nodes via one hop.

The rest of the paper is organized as follows. In Section II, we illustrate data delivery procedure and CSMA/CA algorithm in 802.15.4 MAC. In Section III, we overview the related work on performance evaluation of 802.15.4 MAC. In Section IV, discrete-time Markov chain models are proposed for CSMA/CA and DDP. In Section V, the performance is evaluated via both analytical and simulation work. And finally, we summarize our work in Section VI.

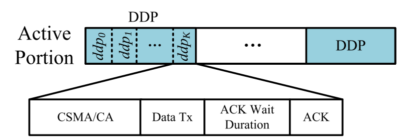

Figure 1. Data delivery procedure in active portion

II. DATA DELIVERY PROCEDURE

IEEE 802.15.4 MAC sublayer provides beacon-enabled and non-beacon-enabled operations. Our attention in this paper is drawn to the beacon-enabled one. Also, the MAC allows the superframe with both active portion and inactive portion [1]. In inactive portion, the node turns into sleep mode and no data is delivered. we assume that only active portion is available since the maximum performance is concerned in this paper. While in active portion, data packets are delivered via DDP. As shown in Figure 1, each DDP involves $(macMaxFrameRetries + 1)$ times of sub-DDP, namely, ddp. The parameter, $macMaxFrameRetries$, implies the maximal number of retransmission of the packet [1]. For simplicity, we use K and k to indicate $macMaxFrameRetries$ and the times of ddp, respectively, namely, ddp_k, where $k = 0, \cdots, K$. Data packets shall be delivered if ddp_k is successfully carried out, involving CSMA/CA, Data Tx and ACK. In addition, there is a constant, IFS (Inter-Frame Space) [1], between the successful delivered data and the consecutive delivery. It can be neglected and not considered in this paper. Any failure of ddp_k results in ddp_{k+1}. All probabilities in this paper are assumed to be obtained based on the steady state.

The parameters in DDP are set by MLME (MAC Layer Management Entity). After the data delivery is notified by MLME, the times of ReTx, k, is initialized to be zero, data shall be maximally repeated $(K + 1)$ times of ddp, until `SUCCESS` is made. Otherwize, `FAILURE` is notified. In other words, K is one of the key factors to determine the performance.

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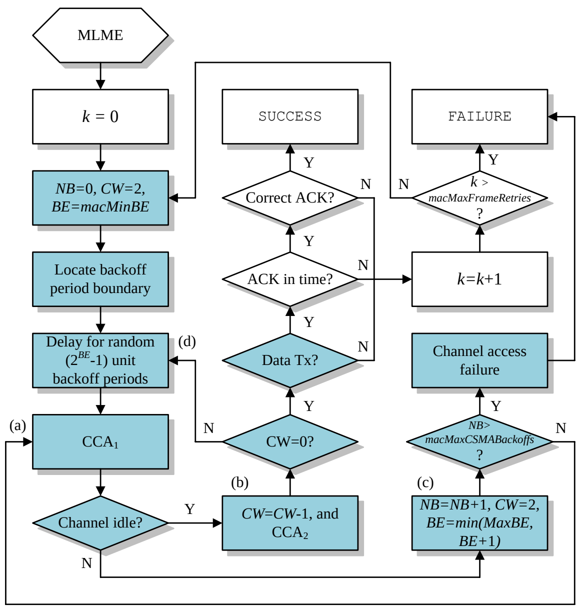

Figure 2. Data delivery procedure, including CSMA/CA algorithm (in shade boxes)

The mechanism of CSMA/CA is the key component in 802.15.4 MAC, shown in the shade boxes in Figure 2. It is adopted to arrange the nodes in the network with an appropriate order when they access the channel. It starts from the notification issued by MLME, and ends when the channel is found either idle or busy. In brief, two behaviors are involved in this algorithm, backoff period (BP) delay and twice CCAs (Clear Channel Assessment). Herein, for the simplicity, we denote them as once $BP-CCA-CCA$. The following gives the details.

After the k initialization, the node firstly perform a ***BP***, as shown in Figure 2. The length of ***BP*** is a random value based on the period determined by BE, namely, $(2^{BE}-1)$ units of $aUnitBackoffPeriod$, that is, 20 symbols. Then MAC starts to count down the time prior to the first CCA.

Then the first CCA shall be performed at the boundary of the backoff period, as (a) implies in Figure 2. If the channel is accessed idle, CW self-deceases by one and CCA shall be performed again (see (b) in Figure 2). If this second CCA successfully finds the channel idle, then the CSMA/CA is successful and data shall be transmitted.

However, if the channel is found busy at the first CCA (see (c) in Figure 2), MLME enables the next ***BP*** with a new length, determined by an updated BE, where $BE = min(MaxBE, BE+1)$. Or if the channel is idle in CCA_1, while busy in CCA_2, namely $CW = 0$, then MLME activates a new first CCA in the next round of ***BP*** (see (d) in Figure 2). If both the twice CCAs find the channel busy, a notification of `FAILURE` is indicated by MLME and forwarded to the *Upper Layers* [1].

CSMA/CA algorithm consists of NB times of $BP-CCA-CCA$ procedures, where the length of BP is determined by BE, and the potential number of CCA is determined by CW, as follows,

- NB: the number of times the CSMA/CA algorithm shall be required to backoff while attempting the current transmission. $0 \leq NB \leq macMaxCSMABackoffs$, where $1 \leq macMaxCSMABackoffs \leq 5$, but the default value is 4. NB is initialized 0. In our work, we use Q and q to denote $macMaxCSMABackoffs$ and the number of times, namely, $q = 1, \cdots, Q$, where $Q = macMaxCSMABackoffs$.
- CW: the contention window length, defining the number of backoff periods that need to be cleared of channel activity before the transmission can commence. In slotted CSMA/CA, by default, the length is set to be 2, namely twice CCA.
- BE: the backoff exponent. It is related to the length of backoff period a node shall wait before attempting to access a channel. The value depends on battery life extension or not, as shown in Figure 2. Here we assume $BE = macMinBE$, where $0 < macMinBE \leq 3$.

III. Related Work

The community has been evaluating the performance of 802.15.4 MAC by simplifying CSMA/CA algorithm (for example, only once CCA in [2], [3]). BE, CW and NB have mostly received specific attention, so has the payload size of data frame, N_{MSDU}. The impact of BE and N_{MSDU} are concerned in [4]–[9], where different methods have been proposed to determine the length of ***BP***. CW is investigated in [2], [8], which concludes a large number of CCA can lead to less throughput. Ramachandran et al. [2] also evaluates the influence of NB. By focusing on CSMA/CA, these methods above claim to involve the whole data transmission procedure. However, this might no be true since CSMA/CA is the beginning of the procedure. ACK and retransmission (ReTx) also need to be concerned.

Quite limited literature has considered the impact of ACK during the data transmission. Much work shows their interest in the difference between with and without ACK. Mišić starts one of the most pioneering work in ACK-related 802.15.4 MAC performance evaluation. The fruitful research has been accomplished in this field including different topology network with ACK (star [10] and cluster [11]), and different transmission in terms of uplink/downlink [12]. However, as mentioned in [2], [13], the analytical models diverse from their simulation results. Reference [13], [14] also concerns the up-link transmission respectively with/without ACK. Particularly in [13], an accurate and scalable analytical model is proposed. However, their work may not be comprehensive enough since only successful ACK is involved.

The work on the impact of retransmission on the network performance is still inadequate. The proof of applying DTMC in the evaluation work has been presented in [3]. Three dimensional DTMC is proposed in [15], [16], where the number of retransmission is taken into account. However, the data delivery procedure in their work might not be illustrated appropriately. Finding channel busy at the first CCA leads to the current CSMA/CA, again. This, in fact, should result in the next CSMA/CA procedure if the maximum times (namely K) of retries have not been met. Jung also proposes a three-type DTMC model to analyze the performance [17]. By considering the inactive portion in the superframe, their work in fact focuses on the unsaturated network. Their contribution of DTMC also includes the probability of deferring the data frame that can not be completed in current superframe to the next superframe. However, in a saturated situation (which is concerned in our work), their method might not be applicable. Though having the impact of different number of retransmissions considered, as mentioned in [13], Jung's work may increase the complexity of the analysis and limits the scalability.

There are also other factors that can affect the performance, including the number of nodes involved in the network, signal fading and interference, and so on. Our previous work has investigated the impact of the number of nodes with both star [18] and tree topology [19], [20], respectively. Channel interference is concerned in this paper, and signal fading will be evaluated in our future work.

In our work, we propose a comprehensive DTMC for 802.15.4 MAC. Our attention is focused on the impact of the maximum number of retransmission, K (namely, $macMaxFrameRetries$). The performance is investigated in terms of network throughput, packet delivery ratio and time delay.

IV. DTMC OF DDP

We illustrate the whole procedure of DDP in Figure 2 via stochastic analysis in terms of the procedure of ddp_k, as shown in Figure 3. The procedure is initialized by $k = 0$ (namely ddp_0). and K times of ReTx (namely ddp_k, $k = 1, \cdots, K$). Each of them involves at most Q times (namely $amacMaxCSMABackoffs$) of $BP - CCA - CCA$, followed by once Tx and once ACK. As shown in this figure, the subscript k in BP, CCA, Tx and ACK indicates the k-th ddp; the subscript, q in BP and CCA, denotes the q-th $BP - CCA - CCA$ procedure; and respectively, i and $i|i$ depict channel $idle$ (in the first CCA) and channel $idle$ at the second CCA, given $idle$ in the first CCA. Also, the superscripts, n and c depict node and channel, respectively.

- ddp_k: the k-th procedure of data delivery. This procedure includes Q times of CSMA/CA, once data transmitting (namely Tx_k) and the behavior of waiting for and processing ACK (namely ACK_k). There are algotether $(K + 1)$ times of ddp_k.

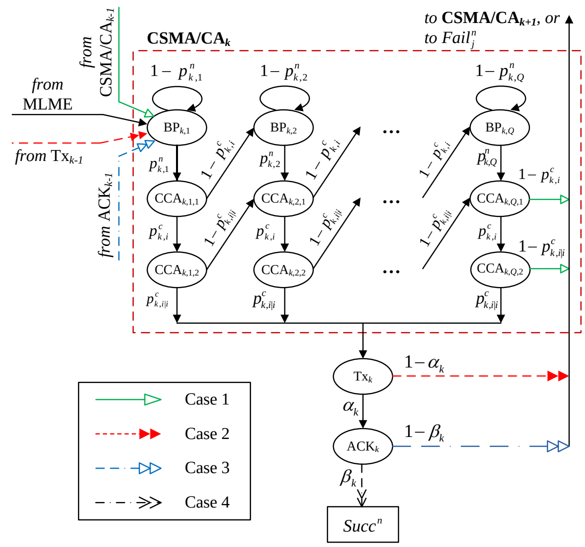

Figure 3. DTMC of DDP and four cases in DDP

- $BP_{k,q}$: the q-th $Backoff\ Period$ in the ddp_k.
- $p^n_{k,q}$: the probability for the node to perform the $BP_{k,q}$.
- $CCA_{k,q,v}$: the v-th CCA in q-th $BP - CCA - CCA$ procedure in ddp_k, where $1 \le v \le CW$, $1 \le q \le Q$. In our work, CW is initialized to be 2.
- $p^n_{k,i}$: the probability that the channel is found $idle$ at the first CCA (namely $CCA_{k,q,1}$), here i denotes $idle$.
- $p^c_{k,i|i}$: the probability that the channel is found $idle$ at the second CCA (namely $CCA_{k,q,2}$), given the $idle$ channel in $CCA_{k,q,1}$.
- α_k: the probability that the transmitting in the PHY sublayer is successful, considering the channel noise or interference.
- β_k: the probability that the correct ACK is received in time.

A. Four Cases in Data Delivery Procedure

We understand CSMA/CA, data Tx in PHY sublayer and ACK-related process can all impact the network performance. Therefore, we take all of them into account, as shown in Figure 3. In each ddp, if the current CSMA/CA is unable to lead to Data Tx, another CSMA/CA in a new ddp shall be processed, which can also be activated by the failure of Data Tx in PHY sublayer. Additionally, if the ACK-related process fails, Data Tx in the new ddp shall be carried out again in the PHY sublayer.

The data is successfully delivered if and only if the **Correct** ACK is received within $macAckWaitDuration$, namely 54 symbols [1]. A notification of `SUCCESS` is generated by MLME. Otherwise, a notification of `FAILURE` occurs. These four cases are,

- Case 1: unsuccessful data transition due to the failure of CSMA/CA; or

- Case 2: unsuccessful data transition, due to the channel failure (noise or interference); or
- Case 3: the data is successfully transmitted, but **No** ACK is received within the certain period of time ($macAckWaitDuration$ symbols); or, received in time, but the ACK is **Incorrect**. In other words, the DSN (Data Sequence Number) this ACK contains is not same with the one from the data or MAC command that is being acknowledged [1]; or
- Case 4: successful data transmission and correct ACK received in time.

Based on Figure 3, we can have the probabilities for Case 1 - Case 4 in DDP, denoted as $p^n_{c_1}, \cdots, p^n_{c_4}$, respectively, as follows,

$$\begin{aligned} p^n_{c_1} &= \sum_{k=0}^{K}[(1-p^c_{k,i}) \cdot \pi(CCA_{k,Q,1}) \\ &\quad +(1-p^c_{k,i|i}) \cdot \pi(CCA_{k,Q,2})], \quad (1) \\ p^n_{c_2} &= \sum_{k=0}^{K}(1-\alpha_k) \cdot \pi(Tx_k), \quad (2) \\ p^n_{c_3} &= \sum_{k=0}^{K}(1-\beta_k) \cdot \pi(ACK_k), \quad (3) \\ p^n_{c_4} &= \sum_{k=0}^{K}\beta_k \cdot \pi(ACK_k). \quad (4) \end{aligned}$$

In addition, we assume the data to be transmitted at each node is subject to Poisson process, with the mean as p. Also, p is the normalized traffic load prior to DDP. And the state of $Fail^n_j$ denotes the j-th failure in DDP, where $j = 1, 2$.

Also the parameter of $p^n_{k,q}$ is assumed as a geometric random variable [2], [3], as shown in (5) [1]. This is consistent with the fact that the lower value of the q can lead to the bigger chance to perform *BP-CCA-CCA*. Furthermore, the BP can be regarded *memoryless*. Meanwhile, the probability of channel failure due to interference or noise, namely $1-\alpha_k$, is also assumed to be subject to the uniformly distributed white noise with $0.8 \leq \alpha_k \leq 1$, where $k = 0, \cdots, K$.

$$p^n_{k,q} = \frac{1}{\frac{2^{BE}-1}{2}+1} = \begin{cases} \frac{2}{2^{q+2}+1}, & \text{if } q = 1, 2; \\ \frac{2}{2^{Q}+1}, & q = 3, \cdots, Q. \end{cases} \quad (5)$$

Meanwhile, we note that CCA behavior is actually independent to the procedures of data delivery because CCA is determined by the channel state. In other words, The probability of $p^c_{k,i}$ is assumed to be the same at different ddp_k. Therefore it is rewritten as p^c_i. And so is the probability of $p^c_{k,i|i}$, rewritten as $p^c_{i|i}$. Moreover, since all the probabilities in our DTMC is assumed to be obtained in the steady state, we use π to denote the steady state, followed by the MAC behavior or channel state. Therefore, the steady state of BP, *CCA*, Tx, ACK, $Fail$, and $MLME$ can be obtained.

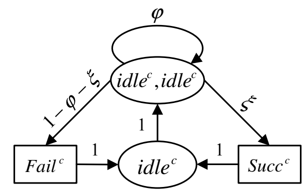

Figure 4. Channel DTMC

B. DTMC of Channel

The physical channel plays a vital role in the evaluation. This is not only because of the potential noise and interference which has been considered in Case 2 in Section IV-A, but also the fact that the channel states (*idle* or *busy*) determine whether the data transmission can be carried out in the first place.

Furthermore, we understand the fact that all frames, including data, command, and ACK, are transmitted via the physical channel. Therefore, the throughput of the network can actually be equal to the throughput of the channel. This can be more reliable than the throughput at nodes or the network coordinator. Unlike the latter which has been adopted in most work in this field, we investigate the network performance via the evaluation on the channel.

Two states are shared by both nodes and the channel, namely $idle$ and $(idle, idle)$. Regarding twice CCAs, $idle^c$ and $(idle^c, idle^c)$ are introduced to facilitate the modeling by combining both MAC process and channel states, where the superscript c refers to $channel$, as shown in Figure 4. The probabilities are illustrated in (6) and (7) respectively.

$$p^c_i = \frac{2-\varphi}{1+(N_{MSDU}+1)(1-\varphi)}, \quad (6)$$

$$p^c_{ii} = \frac{1}{1+(N_{MSDU}+1)(1-\varphi)}. \quad (7)$$

For the channel, these two states lead to the result of either `SUCCESS` or `FAILURE`, denoted by $Succ^c$ and $Fail^c$ in Figure 4. Here, the number of times is not applied to the latter, unlike j in $Fail^n_j$. Assume M source nodes in the network, the probability from $(idle^c, idle^c)$ to $Succ^c$ is,

$$\xi = Mp^n_{t|ii}(1-p^n_{t|ii})^{M-1}, \quad (8)$$

owing to that each time only one source node can successful transmit data frames via the channel. Also, staying at $(idle^c, idle^c)$ means no transmission from source nodes in the network, namely,

$$\varphi = (1-p^n_{t|ii})^M, \quad (9)$$

where $p^n_{t|ii}$ is the probability of transmitting the packet after the successful twice CCA. This parameter is obtained by (10)

$$p^n_{t|ii} = \frac{p^n_t}{p^c_{ii}}. \tag{10}$$

Particularly, we have $0 \leq p^c_{t|ii} \leq 1 - \sqrt[M]{\frac{2}{N_{MSDU}+1}}$, considering both $\varphi > 0$ and $p^n_{t|ii} > 0$.

V. Numerical Results

We assume the network be comprised by thirty homogeneous source nodes, namely $M = 30$. They are sending data to a coordinator node. Based on ns-2, the distance between the nodes and the coordinator is randomly distributed within the working range (15 m) so that the nodes can talk to the coordinator with a single hop. These nodes need to deliver a packet of 100-byte MSDU (namely $N_{MSDU} = 100$ byte) each time with normalized traffic load p. Particularly, since three CSMA/CA-related parameters, BE, CW and NB, have been sufficiently studied by the research community, their impact shall not be addressed. Our work emphasizes on the impact of K ($macMaxFrameRetries$). We evaluate the network performance in terms of network throughput, time delay and packet delivery ratio, as follows:

- $thpt$: the effective network throughput. Namely, the ratio of the MSDU received at the coordinator to the consumed time. In particular, SHR ($Synchronization\ Header$), PHR ($PHY\ Header$), MHR ($MAC\ Header$) and MFR ($MAC\ Footer$) are not concerned, neither the command frames such as beacons [1].
- t_{delay}: the average time consumed when a packet is successfully transmitted from the source node to the coordinator.
- η: the packet delivery ratio. That is, the ratio of the number of MSDU received at the coordinator to the one sent from the nodes.

We begin the evaluation with the probability of Case 1 to Case 3 (refer to (1), (2) and (3)), shown in Figure 5.

In Figure 5, we observe that Case 1 brings the prominent impact to the network. That is, ReTx occurs mostly due to the busy channel during twice CCA. Particularly, the first CCA has a stronger impact on the performance, because the probability of the CCA_1 is much larger than the one of CCA_2, namely, $\frac{\sum_{k=0}^{K}\sum_{q=1}^{Q}\pi(CCA_{k,q,1})}{\sum_{k=0}^{K}\sum_{q=1}^{Q}\pi(CCA_{k,q,2})} \gg 1$.

Obtaining $thpt$ via the channel states can also be found in [2], [3]. However, only CSMA/CA is involved in their work. The throughput in [2], [3] is actually based on the successful transmission at source nodes, rather than channel-based analysis in our work. Also, their throughput involves data packets, ACK frame, beacon frame and other maintenance frames, which did not depict the effective throughput contributed by MSDU. In our work, we are concerned

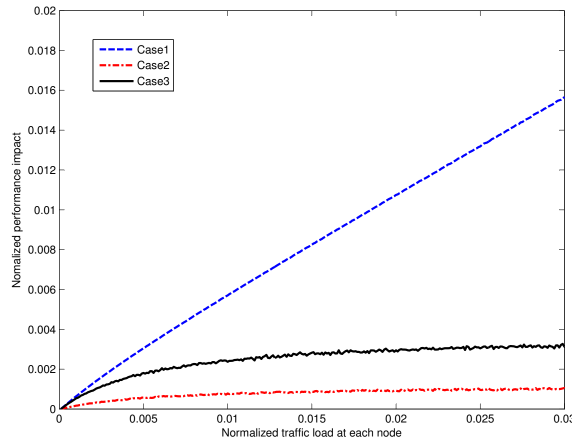

Figure 5. Normalized performance impact of case 1 to case 3

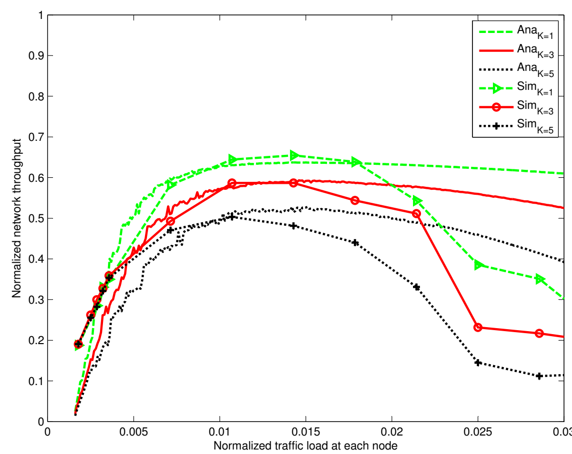

Figure 6. Normalized network throughput at different K

about the throughput due to the data packets only, and recognize that channel noise/interference and ACK-related cases should also be considered. Therefore, given $\pi(Succ^c)$, the probability of Case 4, i.e. $p^n_{c_4|s^c}$, is,

$$p^n_{c_4|s^c} = \frac{p^n_{c_4}}{(K+1)\cdot\pi(Succ^c)}. \tag{11}$$

Now the network throughput is obtained, as illustrated in (12). The throughput at different $maxMaxFrameRetries$ (i.e. K) is shown in Figure 6 .

The analytical results are also verified by the simulation results based on $ns-2$. First, more procedures of ddp_k bring less throughput, because these procedures prolong the packet delivery time. Second, throughput behaves with a saturation interval, as shown in Figure 6. After the saturation, throughput decreases. This is because more packets may have been dropped due to collision.

The total time delay, denoted by t_{sum}, is obtained, as follows,

$$thpt = p^n_{c_4|s^c} \cdot \frac{N_{MSDU} \cdot \pi(Succ^c)}{\pi(idle^c) + \pi(idle^c, idle^c) + N_{MSDU} \cdot \pi(Succ^c) + N_{MSDU} \cdot \pi(Fail^c)} = p^n_{c_4|s^c} \cdot \frac{N_{MSDU} \cdot M \cdot p^n_{t|ii} \cdot (1 - p^n_{t|ii})^{M-1}}{1 + (N_{MSDU} + 1)(1 - (1 - p^n_{t|ii})^M)}. \quad (12)$$

$$t_{delay} = \sum_{k=0}^{K} t_k, \quad (13)$$

where t_k is the time consumed during the ddp_k procedure, as shown in (14),

$$t_k = \sum_{q=1}^{Q} \{\pi(BO_{k,q}) \cdot \tau_{BP} + \sum_{v=1}^{2} [\pi(CCA_{k,q,v}) \cdot \tau_{CCA}]\} + \pi(Tx_k) \cdot \tau_{Tx} + \pi(ACK_k) \cdot \tau_{ACK}, \quad (14)$$

where τ_{CCA}, τ_{Tx}, τ_{ACK} and τ_{BP} are illustrated in (15) to (19), respectively.

$$\tau_{CCA} = 8 \cdot 0.016 = 0.128 \text{ ms}, \quad (15)$$

$$\tau_{Tx} = \frac{MSDU}{Datarate} = \frac{100 \cdot 8}{250} = 3.2 \text{ ms}, \quad (16)$$

$$\tau_{ACK} = macAckWaitDuration + t_{ACK} \quad (17)$$

$$= 0.864 + 0.352 = 1.216 \text{ ms}. \quad (18)$$

$$\tau_{BP} = \begin{cases} 0.32 \cdot (2^{BE} - 1), & \text{if } macMinBE \leq BE \leq 4; \\ 0.32 \cdot (2^{aMaxBE} - 1), & \text{if } BE > 4. \end{cases} \quad (19)$$

where 0.32ms is the length of $aUnitBackoffPeriod$. And t_{ACK} means the time to process the received ACK. By varying K, we have Figure 7.

When K becomes higher, the node spends more time on delivering the packet to the coordinator. Furthermore, the time delay increases significantly at higher traffic load due to collision.

The packet delivery ratio η is illustrated in (20). Also we investigate the evaluation by setting different K, as shown in Figure 8.

$$\eta = \frac{thpt}{M \cdot p \cdot N_{MSDU}} = \frac{p^n_{t|ii} \cdot (1 - p^n_{t|ii})^{M-1}}{1 + (N_{MSDU} + 1)(1 - (1 - p^n_{t|ii})^{M-1})} \quad (20)$$

Similar results are obtained in this figures as well. Both analytical work and simulation share the result that delivery ratio is performed in a decreasing trend along the increment of the traffic load. Our simulation also shows that the

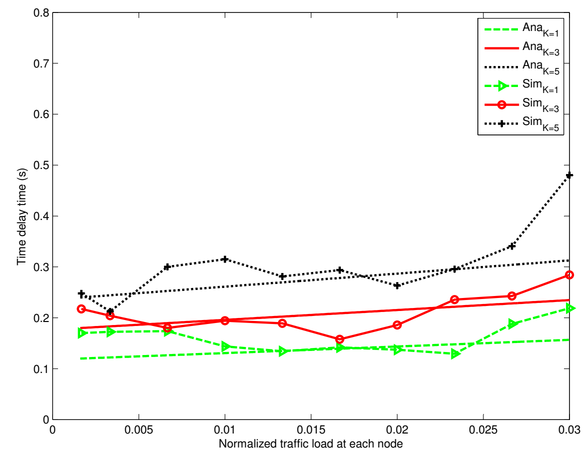

Figure 7. Time delay at different K

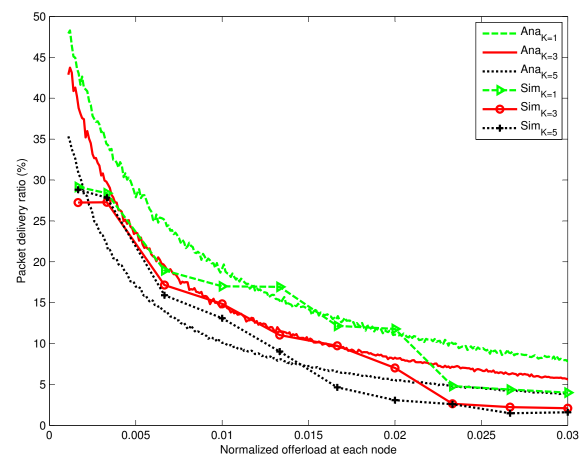

Figure 8. Packet delivery ratio at different K

network relatively keeps enjoying the high ratio when the traffic load is fairly small. It reminds that the packet delivery ratio suffers more at higher traffic loads.

VI. Conclusion

We proposed discrete-time Markov chain (DTMC) models for the comprehensive data delivery procedure (DDP) in 802.15.4-based beacon-enabled network. DDP includes ($macMaxFrameRetries$ + 1), namely, (K + 1) times of sub-DDP (that is, ddp_k, $k = 0, \cdots, K$). Each ddp_k involves three MAC behaviors. They are standard slotted CSMA/CA algorithm which is comprised of up to

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$macMaxCSMABackoffs$ times of backoff periods (BP) and twice CCA, the transmission (Tx) in PHY sublayer and ACK-related (Acknowledgment) process as well. The successful data delivery indicates that, during a DDP, the data packet is transmitted after success in all three behaviors. Because of the success/failure of the three MAC behaviors, four cases are proposed regarding different outcomes of data delivery. Based on the DTMC and the simulation work via ns-2, we evaluate the MAC performance of the network. By varying K, the impact on the network performance are studied, in terms of throughput, time delay and packet delivery ratio global. Our work reveals more K can bring poor performance.

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