Energy Efficient Consecutive Packet Transmissions in Receiver-Initiated Wake-Up Radio Enabled WSNs

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***Abstract*— In wake-up radio (WuR)-enabled wireless sensor networks, data communication among nodes is triggered in an on-demand manner, by either a sender or a receiver. For receiver-initiated WuR (RI-WuR), a receiving node wakes up sending nodes through a wake-up call. Correspondingly sending nodes transmit packets in a traditional way by competing with one another multiple times in a single operational cycle. In this paper, we propose a receiver-initiated consecutive packet transmission WuR (RI-CPT-WuR) medium access control (MAC) protocol, which eliminates multiple competitions to achieve higher energy efficiency. Furthermore, we develop two associated discrete time Markov chains (DTMCs) for evaluating the performance of RI-CPT-WuR and an existing RI-WuR MAC protocol. Using the solutions from the DTMC models, closed-form expressions for network throughput, average delay, packet reliability ratio, energy consumption and lifetime, and energy efficiency for both protocols are obtained. Numerical results demonstrate the superiority of the RI-CPT-WuR protocol.**

***Index Terms*— WSNs, IoT, wake-up radio, consecutive packet transmissions, DTMC modeling, performance evaluation.**

I. Introduction

THE advent of 5G has brought faster and seamless connectivity in wireless and mobile communications [1]. One of the 5G based emerging paradigms is the Internet of things (IoT) coupled with wireless sensor networks (WSNs), for developing smart applications such as smart cities, smart grid and smart automation [2]. Particularly, from the recent surge in research on Industry 4.0 and factories of the future, the WSNs integrated with industrial IoT have been an important technology for industrial automation, industrial monitoring, and control applications [3], [4]. When developing protocols for IoT applications, deterministic delivery, reliability, and energy efficiency are usually key design parameters [5], [6].

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As a crucial resource, the battery capacity of IoT devices is fixed and cannot be recharged without energy harvesting. To this end, the recently developed wake-up radio (WuR) technology exhibits its convincing superiority for energy consumption [7], [8]. Although there exist techniques such as duty cycling (DC) for energy conservation, WuR revolutionizes the operation of WSN data transmission by allowing nodes work at a power consumption level that is 1000 times lower than that of the traditional radio [9]. A WuR enabled WSN node contains two radios, one main radio (MR) plus one wake-up radio. The MR is primarily responsible for data exchange and the WuR is used to wake up MR. While the WuR is always *on* to receive wake-up calls (WuCs) from any other node [10], the MR is in the *off* or *sleep* mode for most of the time and it is switched to *on* or *active* only when needed. Note that the *active and sleep periods apply only to MRs*. WuCs in WuR are generated in two ways, i.e., either transmitter-initiated (TI) [11] or receiver-initiated (RI) [10]. For RI-WuR, a receiver initiates data transmissions by transmitting a WuC to senders to switch on their MRs.

On the other hand, in order to provide deterministic and reliable communication, a time-division multiple access (TDMA) based medium access control (MAC) protocol could be adopted in many industrial applications [12]. To employ TDMA MAC is expected to render reliable communication for a synchronized network by avoiding competition among nodes. For asynchronous networks, however, enabling contention-based MAC protocol similar to carrier-sense multiple access with collision avoidance (CSMA/CA) is a better option for improving medium utilization. In CSMA/CA, only active nodes (with data packets to transmit) contend and the other inactive nodes do not participate in access competition [13]. Thus medium utilization is higher in CSMA/CA at a cost of lower reliability due to collisions. Clearly, reducing the number of competitions leads to fewer occurrences of collisions, leading to increased data transmission reliability. We take this fact as the motivation to propose a CSMA/CA based protocol for faster and more reliable data communications in WuR enabled WSNs. The protocol is targeted at WSNs in the context of industrial as well as general purpose applications.

In this paper, we propose a receiver-initiated consecutive packet transmission WuR (RI-CPT-WuR) MAC protocol that allows a node transmit multiple packets one by one

TABLE I

A FEW STATE-OF-THE-ART WUR MAC PROTOCOLS VERSUS RI-CPT-WUR: A QUALITATIVE COMPARISON

Features	SNW-MAC [31]	AWD-MAC [32]	DoRa [33]	BoWuR [11]	OPWUM [34]	ALBA-WuR [9]	RI-CPT-WuR [This work]
Packet generation of nodes	No	No	No	No	No	No	Yes
Simulations	No	Yes	Yes	No	Yes	Yes	Yes
Experimental validation	Yes	No	No	No	No	No	No
Mathematical analysis	No	No	No	Yes	Yes	No	Yes
Collision avoidance (by)	No	No	No	CCA/BO	CCA/BO/ RTS/CTS	RTS	BO
WuC transmission mode	Unicast	Broadcast	Unicast	Unicast	Broadcast	Multicast	Broadcast
Network scenario	Star	Star	Star	Star	Tree	Distributed	Star
Communication mode	RI	RI	RI	TI	RI	TI	RI

† Abbreviations: Clear channel assessment (CCA); backoff (BO); request to send (RTS); and clear to send (CTS). For protocol acronym, refer to each reference paper for details.

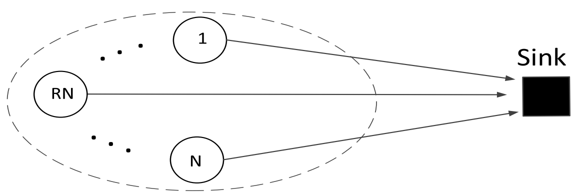

Fig. 1. Illustration of a WuR enabled WSN cluster with N contending nodes plus one sink node as the common receiver.

consecutively after winning an access competition. In other words, RI-CPT-WuR MAC enables transmitting multiple packets through a single competition, whereas a competition is always needed for each packet transmission when a traditional RI-WuR is employed. Hence, RI-CPT-WuR provides fast packet delivery and is highly reliable in comparison with RI-WuR. Moreover, RI-CPT-WuR allows other nodes to sleep during the period when the medium is occupied by the sending node in order to boost energy efficiency.

Furthermore, we develop a set of two associated discrete time Markov chains (DTMCs) to model both RI-WuR and RI-CPT-WuR MAC as Markov chains are popular for modeling IoT MAC protocols [14]. One of these two DTMCs captures the queuing nature of packets in a reference node (RN) while the other one models the number of active nodes in the same cluster, hereafter referred to as *node* DTMC and *system* DTMC respectively. Furthermore, we illustrate the way how those DTMCs are operated jointly to incorporate with each other for evaluating network performance. Using the solution obtained from DTMC modeling, we perform analysis for five performance metrics and validate the accuracy of the models via discrete-event simulations.

In this study, we model RI based MAC protocols for WuR enabled WSNs for intra-cluster data communication, as shown in Fig. 1. To the best of our knowledge, this is the first effort to develop analytical models *for multiple competitions in a cycle for receiver-initiated MAC protocols in WuR enabled WSNs*. A summary of the main contributions is as follows:

- A receiver-initiated consecutive packet transmission MAC protocol for WuR embedded WSNs is proposed. A salient feature of RI-CPT-WuR MAC is that it reserves the medium for a node to transmit multiple packets consecutively. Therefore, it needs fewer competitions to deliver all packets from all competing nodes.
- Two DTMC models to evaluate the performance of RI based WuR protocols are developed. The *node* DTMC models the queuing nature of consecutive packet transmission by a node whereas the *system* DTMC models the evolution of the active nodes in the network. Then these two DTMCs are integrated in order to model the behavior of consecutive packet transmissions via multiple competitions in one cycle.
- Closed-form expressions for calculating network throughput, mean packet delay, packet reliability ratio, energy consumption and lifetime, and energy efficiency are obtained based on the proposed models. Furthermore, the analytical model has been shown to be very accurate, validated via discrete-event based simulations.

The rest of this paper is organized as follows. After summarizing the related work in Section II, we present the network scenario and protocol design in Section III. The DTMC models are developed in Section IV. Then, expressions for performance metrics are derived in Section V. In Section VI, we present the numerical results obtained by the proposed analytical model and discrete-event simulations. Finally, the paper is concluded in Section VII.

II. RELATED WORK

In recent years, WuR is increasingly gaining its popularity as it provides ultra-low energy communication by diminishing energy consumption due to idle listening and overhearing in traditional DC WSNs [9], [10]. However, overhearing could still happen during the data transmission phase when existing WuR MAC protocols are employed in a network with multiple contending nodes. In many WuR implementations, the WuC is transmitted as a unicast message in order to wake up an intended node. This type of WuC transmissions adopts a polling-based mechanism. In this paper, we analyze broadcast-based WuC transmissions, in which all nodes wake up simultaneously after a common WuC is received and those nodes which have at least one packet to transmit will compete with each other for channel access. If a node does not have any packet to transmit, it will go to sleep immediately. In Table I above, we make a qualitative comparison of a few popular WuR protocols versus RI-CPT-WuR which is proposed in the paper. On the other hand, it is also imperative to develop transmitter-initiated WuR protocols. As an effort towards this direction, we have proposed three protocols in another recent paper [35].

For performance evaluation, there exist many analytical models in the literature for evaluating MAC protocols in WSNs. For instance, a few DTMC models were developed to evaluate synchronous MAC protocols which employ common awake scheduling for packet transmissions in DC WSNs [15]–[17]. Moreover, a multiple packet transmission scheme was analyzed in [18] for synchronous DC MAC protocols with a limited number of slots for access competition. Recently, two analytical models [19], [20] were proposed to evaluate asynchronous MAC protocols such as RI-MAC protocol [21] in which nodes follow their own wake-up schedules. However, the aforementioned models are not suitable to model the WuR based MAC protocols.

For performance evaluation of WuRs, existing contributions are mainly based on simulations and testbeds, with few mathematical models. For example, a simulation based performance evaluation was performed in [9] and [10] including both TI- and RI-WuR MAC protocols. When it comes to modeling of protocols leveraging WuR, merely TI-WuR protocols were modeled so far. For example, a DTMC was developed to model backoff enabled TI-WuR based WSNs in [11], assuming the same contention window size in every cycle. Similarly, an absorbing Markov chain model was developed for analyzing TI-WuR in [14] and [22]considering that the number of failures follows a geometric distribution. However, that model was developed from a single node point of view, not based on the actual MAC level competition among multiple nodes. Moreover, TI-WuR was analyzed mathematically in [23] but collisions that could occur in packet transmission were neglected in their analysis.

To analyze RI-WuR, a common approach in the literature is to adopt the RI-MAC protocol [21] directly over WuR. Although there exist few mathematical models including [19] to analyze the RI-MAC protocol, so far no analytical model is proposed to analyze RI-MAC combined with WuR. Later on in this paper, we model both the RI-WuR and our proposed RI-CPT-WuR MAC protocols using DTMCs. For performance evaluation, many models were developed for networks under saturated conditions [11], [14]. In case of low data rate applications, such as industrial or field monitoring scenarios, it might be possible that there are no or few sensed data packets available during certain reporting cycles.

Our developed modeling framework captures this phenomenon and studies both unsaturated and saturated network conditions. Furthermore, these models are applicable to data transmissions where nodes need to compete each time for a single packet transmission, as well as transmitting packets consecutively through a single competition. When a node transmits multiple packets consecutively, it could occupy medium until all of its packets are delivered. Then it becomes inactive after this CPT. Consequently, there would be a lower number of competing nodes in the rest of a cycle. Our modeling framework incorporates this active node evolution in order to get a complete picture for a network-level analysis.

III. Network Scenario and WuR MAC Protocols

In typical IoT data reporting and collecting scenarios, a sink node receives sensed data from multiple sensor nodes. Consider a cluster of N sensor nodes that transmit packets towards a common one-hop away sink node, as shown in Fig. 1. This section presents the operation of receiver-initiated WuR MAC protocols in such a network. After a WuC which is sent as a *broadcast* message is received, the sending nodes compete with each other for channel access following the CSMA/CA mechanism. For performance analysis of our protocols, we assume first an error-free channel and then extend it to an error-prone channel.

A. Overview of the RI-WuR MAC Protocol

When the original RI-MAC is applied to WuR enabled WSNs, it is referred to as RI-WuR MAC. In the RI-WuR protocol, it is the receiver that initiates the procedure for a data transmissions. When a receiving node is ready to collect data, it broadcasts an unaddressed WuC via its MR to all nodes in the same cluster. The duration between two WuC generations will be calculated in Section V. Upon receiving a WuC, all nodes switch on their MRs and follow a backoff mechanism for channel access competition. Then the winning node transmits a packet successfully. The receiving node informs the reception status and triggers a new transmission using a broadcast message called beacon (B). If a sending node does not have any packet to transmit, it turns off its MR immediately. The receiving node switches its MR off when there is no response to the sent B, i.e., in case of either the last active node has finished its transmission or there is no active node at the time when a B message is sent.

The operation of RI-WuR is illustrated in Fig. 2. For the ease of illustration, we divide the *active* period, excluding WuC, of a receiver into *slots* where one slot is configured as the duration for transmitting a DATA packet and a beacon along with a contention window (CW) duration. Nodes compete in every slot as long as they have packets in their queues. Consider an arbitrarily selected node as the RN and assume that the RN is the winner in the first slot. After gaining channel access, the RN transmits *one* packet to the sink node. Then the second slot starts. As an example shown in Fig. 2, packet transmission will not take place in the second slot due to a collision. In case of a collision, B informs the unsuccessful reception of the sent packet. The packet transmission continues to the third slot with another node, Node 1 as the winner. A sending node's *sleep* period starts after the transmission of its last packet. Thus, each node contains its own awake duration in a cycle depending on the queue length. Accordingly, the receiving node sleeps after completing the data exchange with the longest awaken node, Node 2 in Fig. 2.

B. Operation of the RI-CPT-WuR MAC Protocol

In a network or a network cluster containing multiple nodes, all nodes that have packets to transmit contend in every operational slot for channel access in order to send their packets

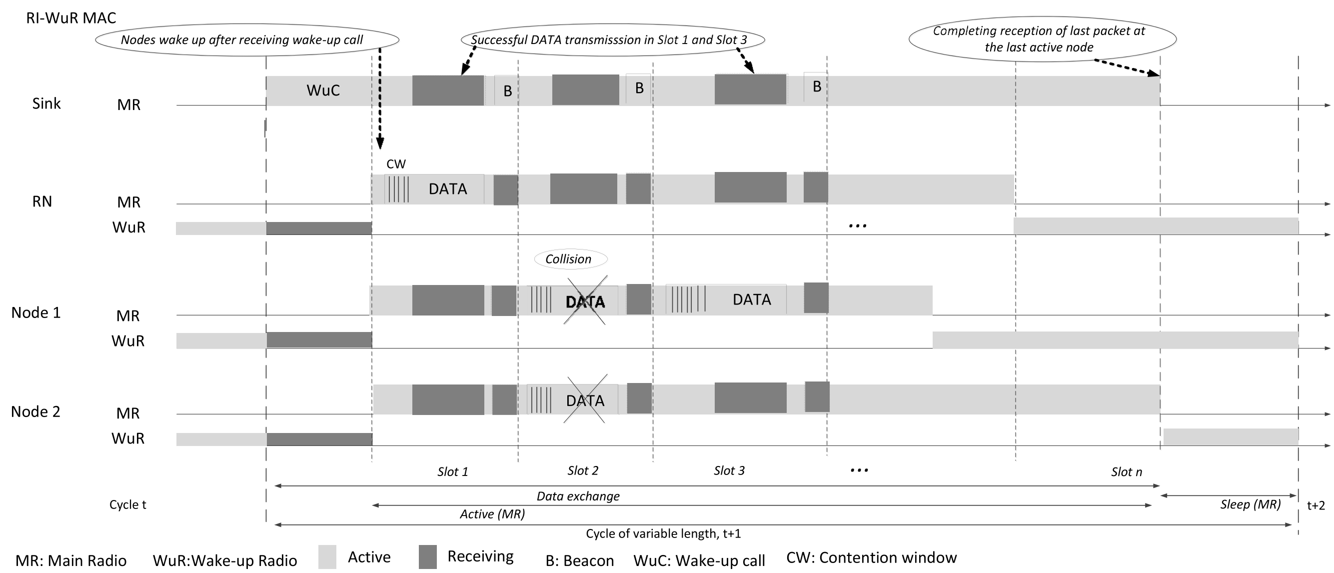

Fig. 2. Illustration of performing packet transmissions in RI-WuR MAC where each *active* period consists of multiple competing slots. Node's *sleep* period starts after transmitting its last packet. The sink node goes to sleep after receiving the last packet of the last active node.

when RI-WuR is employed. However, only one node wins channel access and transmits. Meanwhile the other contending nodes need to listen to the ongoing packet exchange. There are two disadvantages with this approach. Firstly, the same amount of energy is consumed by the nodes other than the winning node due to overhearing. Thus substantial energy is wasted for those nodes which lost access contention. Secondly, a node has to compete in every slot as long as it has a packet to transmit. Consequently, more collisions would occur, reducing the reliability of packet delivery. To address these two problems, we propose below an RI-CPT-WuR protocol to improve energy efficiency and reliability for data transmission in WuR enabled WSNs.

The main idea of RI-CPT-WuR is to reserve the medium in subsequent slots based on the queue size of the winning node for multi-packet transmissions. When the sink node initiates a data collection procedure by a WuC message, all sending nodes turn on their MRs to participate in channel access competition. The winning node captures the medium and sends its first packet from its queue of length q packets. After receiving this packet and an acknowledgment beacon from the sink, all other nodes go to sleep for the next $q - 1$ slots. Thus, the next competition takes place after $q - 1$ slots and the current winning node will not participate in the next competition. In case of a collision from the first round, access competition will resume in the next immediate slot since the B message from the sink informs failed reception of the packet. Note that a B message is always needed after each DATA packet transmission no matter the onging transmission was successful or not.

The operation of RI-CPT-WuR is illustrated in Fig. 3, based on an example with $Q = 3$ and $N = 3$. Note that while Q represents *the maximum queue size*, q refers to *the queue length of the RN*, and $q \leq Q$. Assume that the RN with $q = 3$ is the winner in the first slot. It transmits *three* packets consecutively to the sink node. After the first packet transmission, all other nodes go to sleep for the next 2 slots. A new round of access competition starts in Slot 4 however with only two nodes since the RN has become inactive. It is shown that another competition in Slot 5 with Node 2 as the winner, since a collision happened in Slot 4. Finally, Node 2 with $q = 1$ is the only remaining node in Slot 7 and it sends its packet. Afterwards both the sink and Node 2 go to sleep.

IV. DTMC Models

In this section, we first introduce DTMC modeling and explain its applicability to DC MAC protocol analysis. Then, we develop two DTMC models and integrate those models jointly in order to calculate successful transmission probability.

A DTMC model represents a stochastic process containing a finite space with multiple states in which a state transition occurs with a probability dependent only on the most recent transition. A state in the DTMC evolves at each time step. All state transitions happen based on the probability of occurring events like arrivals and departures. At each state, the summation of exiting probabilities is equal to 1 and the stationary probabilities $\boldsymbol{\pi}$ are obtained by

$$\boldsymbol{\pi} = \boldsymbol{\pi P}, \quad \boldsymbol{\pi e} = \mathbf{1}, \tag{1}$$

where $\boldsymbol{\pi}$ is the stationary distribution vector and $\boldsymbol{e}$ is a column vector of ones.

The DTMC based modeling approach suits well for analyzing DC MAC protocols [24]. This is because protocols following DC have periodicity in the time domain, allowing to partition the observation time into cycles. Each cycle has *on* duration to perform data exchange activities while the rest of the cycle is off. As DC MAC protocols have discrete periods of time and events (arrivals and departures) occur in the *on* duration of every cycle, it is straightforward to apply DTMCs in order to evaluate the performance of such protocols.

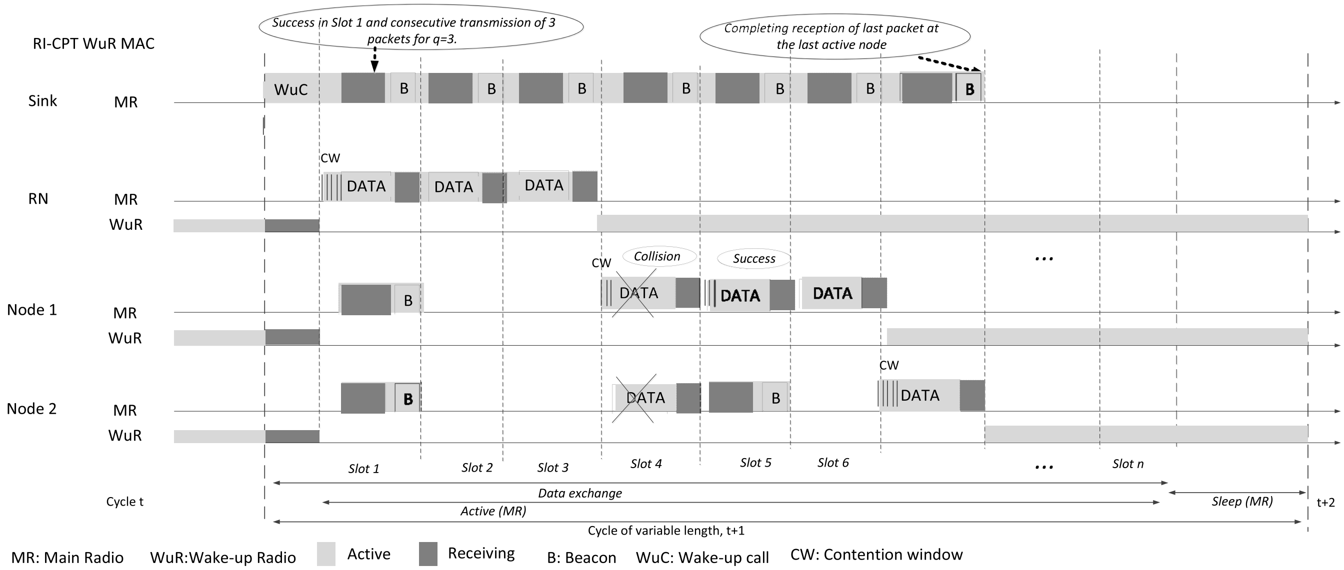

Fig. 3. Illustration of performing consecutive packet transmissions in RI-CPT WuR MAC where each *active* period consists of q reserved slots by the winning node with q packets. A node goes to sleep if it has lost the competition for the next $q-1$ slots. Note that the nodes compete in the next immediate slot after occurring a collision, however, the previous winning node would not participate in this competition.

A. Node DTMC for RI-WuR

The *node* DTMC models the evolution of the number of packets over time in the queue of the RN with respect to transmissions and arrivals. Denote the arrival rate by λ. Then the probability that i packets arrive into a node queue during a cycle of length T is $A_i = (\lambda T)^i \cdot e^{-\lambda T}/i!$. In RI-WuR, the cycle length, T, is variable as to be explained in Sec. V. We calculate correspondingly the average cycle duration and incorporate it into the models. The probability of arriving i or more packets during T is $A_{\geq i} = 1 - \sum_{j=0}^{i-1} A_j$. Let $P_{(i,j)}$ be the probability of finding j packets in the queue at cycle $t+1$, conditioned on that i packets are available in the queue of the RN at cycle t. Furthermore, the probability of transmitting packets successfully in i slots with a probability p_s out of $m+1$ slots would be $\binom{m}{i-1} p_s^i (1-p_s)^{m-i+1}$.

As an example, the transition probability from State i to State j is explained as follows. $P_{(i,j)} = \sum_{m=i-1}^{n-1} \binom{m}{i-1} p_s^i (1-p_s)^{m-i+1} \cdot A_j$ is the probability of occurring i successful transmissions, i.e., i slots successfully, when RI-WuR is configured with n maximum number of competing slots and receiving j packets during a cycle for $i = 0, ..., Q$ and $j = 0, ..., Q$.

B. System DTMC for RI-WuR

The evolution of the number of active nodes in the network is modeled by the *system* DTMC. Let $P'_{(k,l)}$ be the probability that l active nodes compete in Cycle $t+1$, conditioned on that k active nodes competed in Cycle t. When k nodes are active in a slot of a cycle, the probability for occurring a successful packet transmission is $S_k = kP_{s,k-1}$ and for happening a collision is $\widehat{S_k} = 1 - S_k$. With a successful transmission, a node's queue might become empty if there is only one packet before the transmission or it might still be active when there are at least two packets in total. Then, the probability of the RN's queue being empty in case of a successful transmission occurred with a probability p_s is $P_e = p_s A_0 \pi_1 / p_s (1-\pi_0)$ and $\widehat{P_e} = 1 - P_e$ is the probability that it would not be empty. Here, π_0 and π_1 are the steady state probabilities for having 0 and 1 packet in the queue, respectively. Denote $X_k = S_k P_e$, $\widehat{X_k} = \widehat{S_k} + S_k \widehat{P_e}$. Consider that $B_k(l) = \binom{l}{k} \widehat{A}^k A_0^{l-k}$ is the probability that k out of l nodes become active in a cycle, where $\widehat{A} = 1 - A_0$.

The transition probabilities of the *system* DTMC are defined in Table III. The transition probability, $P'_{(k,l)} = \prod_{r=0}^{k-1} X_{k-r} \cdot \prod_{r=0}^{k-1} \cdot [\sum_{\upsilon=0}^{k-1} \widehat{X}_{k-\upsilon}] \cdot B_l(N)$, can be explained as follows. From the above paragraph, it is clear that X_k is the probability of occurring a state reduction by 1 in the *system* DTMC, i.e., the number of available active nodes for competition in the next slot is $k-1$. Moreover, $\widehat{X_k}$ is the probability of occurring no change in a state due to either a successful transmission but the node is still active or the node is not contending in the slot since it has no packet. Then, $\prod_{r=0}^{k-1} X_{k-r}$ gives the probability that the competition succeeded and nodes go empty in k slots and no state change occurs in the other $n-k$ slots with the probability of $\prod_{r=0}^{k-1} \cdot \sum_{\upsilon=0}^{k-1} \widehat{X}_{k-\upsilon}$. Furthermore, $B_l(N)$ is the probability that l out of N inactive nodes become active. Finally, the product of all the above explained probabilities gives $P'_{(k,l)}$ for $k = 0, ..., N$ and $l = 0, ..., N$.

C. DTMC Models for RI-CPT-WuR

Recall that the key feature of the RI-CPT-WuR MAC protocol is to transmit all packets that a node has consecutively once it wins a channel access competition. Accordingly, the *node* DTMC is modified as mentioned in Table IV. In this table, $\binom{m}{0} p_s (1-p_s)^m \cdot A_j$ is the probability of performing 1 successful transmission out of $m+1$ slots as one successful contention is enough to transmit all packets in a cycle for a node. Then, the node status becomes idle and it would not participate in the next competition.

TABLE II

TRANSITION PROBABILITIES OF THE NODE DTMC

$$\begin{aligned} &P_{(0,j)} = A_j\,; \quad 0 \le j < Q\,, \qquad P_{(0,Q)} = A_{\ge Q}\,, \\ &P_{(i,j)} = \textstyle\sum_{m=i-1}^{n-1} \binom{m}{i-1} p_s^i (1-p_s)^{m-i+1} \cdot A_j\,; \\ &\qquad 1 \le i \le Q\,, 0 \le j < Q\,, \\ &P_{(i,Q)} = \textstyle\sum_{m=i-1}^{n-1} \binom{m}{i-1} p_s^i (1-p_s)^{m-i+1} \cdot A_{\ge Q}\,;\ 1 \le i \le Q\,. \end{aligned}$$

TABLE III

TRANSITION PROBABILITIES OF THE SYSTEM DTMC

$$\begin{aligned} P'_{(0,l)} &= B_l\,(N)\ ,\ 0 \le l \le N\,, \\ P'_{(k,l)} &= \textstyle\prod_{r=0}^{k-1} X_{k-r} \cdot \prod_{u=0}^{k-1} \cdot [\sum_{v=0}^{n-k} \widehat{X}_{k-u}^v]\,.\ B_l\,(N)\ ; \\ &\qquad 1 \le k \le N\,,\ 0 \le l \le N\,. \end{aligned}$$

TABLE IV

THE NODE DTMC FOR RI-CPT

$$\begin{aligned} &P_{(0,j)} = A_j\,; \quad 0 \le j < Q\,, \qquad P_{(0,Q)} = A_{\ge Q}\,, \\ &P_{(i,j)} = \textstyle\sum_{m=0}^{n-i} \binom{m}{0} p_s (1-p_s)^m \cdot A_j\,; \qquad 1 \le i \le Q\,, \\ &\qquad 0 \le j < Q\,, \\ &P_{(i,Q)} = \textstyle\sum_{m=0}^{n-i} \binom{m}{0} p_s (1-p_s)^m \cdot A_{\ge Q}\,; \qquad 1 \le i \le Q\,. \end{aligned}$$

TABLE V

THE SYSTEM DTMC FOR RI-CPT

$$\begin{aligned} P'_{(0,l)} &= B_l\,(N)\ ,\ 0 \le l \le N\,, \\ P'_{(k,l)} &= \textstyle\prod_{r=0}^{k-1} S_{k-r} \cdot \prod_{u=0}^{k-1} \cdot [\sum_{v=0}^{n-k} \widehat{S}_{k-u}^v]\,.\ B_l\,(N)\ ; \\ &\qquad 1 \le k \le N\,,\ 0 \le l \le N\,. \end{aligned}$$

Therefore, P_e is not required in the *system* DTMC for RI-CPT-WuR. Correspondingly, the *system* DTMC is modified with S_k instead of using X_k, as mentioned in Table V.

D. The Calculation of p_s

Denote $\{\pi_i\}$ as the stationary distribution of the *node* DTMC and $\{\pi'_k\}$ as the steady state distribution of the *system* DTMC. Both $\{\pi_i\}$ and $\{\pi'_k\}$ can be determined by solving (1) with the transition probabilities from the corresponding tables.

From the *node* DTMC in Table II and (1), $\pi_0\,(p_s)$ is obtained. Similarly, from the *system* DTMC in Table III and (1), $p_s\,(\pi_0)$ is obtained as calculated below. The fraction of cycles where k other nodes and the RN are active, α'_k, is given by

$$\alpha'_k = \binom{N-1}{k} \pi'_{k+1} / \binom{N}{k+1} = (k+1)\,\pi'_{k+1}/N.$$

Then, the probability of having $k+1$ active nodes including the RN in a cycle is

$$\alpha_k\,(\pi_0) = \alpha'_k/G; \quad k = 0, \ldots N-1,\ G = \sum_{k=0}^{N-1} \alpha'_k.$$

When the RN is contending with other k, $0 \le k \le N-1$ nodes, the probability that the RN transmits a packet successfully (successfully or with a failure), is given by $P_{s,k} = \sum_{i=0}^{W-1} \frac{1}{W} \left(\frac{W-1-i}{W}\right)^k$ ($P_{sf,k} = \sum_{i=0}^{W-1} \frac{1}{W} \left(\frac{W-i}{W}\right)^k$), where W is the contention backoff window size. Now, $p_s\,(\pi_0)$ can be expressed as

$$p_s\,(\pi_0) = \sum_{k=0}^{N-1} \alpha_k\,(\pi_0)\,P_{s,k}. \tag{2}$$

Clearly, p_s can be obtained by solving $\pi_0\,(p_s)$ and $p_s\,(\pi_0)$. Hence, both the *system* and the *node* DTMCs should be operated interactively until the solution is converged. In the same way, p_{sf} can be calculated by replacing $P_{s,k}$ with $P_{sf,k}$ in (2).

Similarly, by following the above procedure but using DTMCs in Tables IV and V, both p_s^{cpt} and p_{sf}^{cpt} for RI-CPT-WuR can be calculated.

V. PERFORMANCE ANALYSIS

In this section, we first derive expressions for throughput, delay, packet reliability ratio, energy consumption and lifetime, as well as energy efficiency for the both RI-WuR and the RI-CPT-WuR MAC protocols, and then extend our analysis to error-prone channels. Note that the notations mentioned in the superscript of an expression are corresponding to the respective protocol (*ri* or *cpt*) or radio (*wur* or *mr*).

A. Duration of a Cycle

The duration between two consecutive wake-up calls is referred to as a cycle. As mentioned earlier, RI-CPT-WuR inherits some features of RI-MAC among which the cycle duration is an important metric in addition to the receiver-initiated operation. Therefore, we adopt the same calculation for RI-CPT-WuR as well for the sake of fair comparison. Accordingly, the sleep duration with length L in a cycle is variable and it varies between $0.5L$ and $1.5L$ following the uniform distribution [21]. Correspondingly, each cycle consists of a sleep duration generated randomly in the range of $0.5L$ and $1.5L$. Therefore the average sleep interval of a cycle in this range is given by,

$$sl = (0.5L + 1.5L)/2 = L. \tag{3}$$

In receiver-initiated WuR MAC protocols, the active period depends on the number of configured slots which is decided by the number of retransmissions, R, allowed for a packet, together with N and Q. For a queue size Q and a network of N nodes, the active period contains at most $N \cdot Q \cdot (R+1)$ slots, i.e., $n = N \cdot Q \cdot (R+1)$. According to the operation of RI-CPT-WuR, the length of a cycle, T_c, is given by

$$T_c = n + L. \tag{4}$$

B. Node and Network Throughput

Define the *node throughput*, η, as the average number of packets successfully delivered by a node in a cycle. In both RI and RI-CPT-WuR MAC protocols, a node transmits all packets from its queue in multiple slots of a cycle. The number of packets transmitted in a cycle by a node depends on packet arrival rate λ and the size of its queue, Q. In a cycle, the number of packets that can arrive to a node is $\lambda \cdot T$, while the maximum number of packets that can enter into a node is Q. From the DTMC analysis, η is calculated by,

$$\eta = \sum_{i=1}^{Q} i \cdot \pi_i, \tag{5}$$

where π_i is the probability that i packets are available in the RN's queue. The *achievable network throughput* expressed in packets per cycle is therefore given by

$$Th = N \cdot \eta. \tag{6}$$

C. Average Delay

In this study, we define delay as the number of slots required to deliver η packets successfully in a cycle. In the competition that takes place in a slot, a node wins with a probability p_s. If competition happens in every slot as used in RI-WuR, then the total number of competitions or slots needed to transmit η packets successfully is η/p_s. Differently, RI-CPT-WuR delivers all η packets when winning a competition and avoids $(\eta - 1)$ competitions. In this case, the number of slots used to transmit η packets is $1/p_s^{cpt} + (\eta - 1)$. Therefore, the corresponding average delay per cycle in terms of slots is calculated as,

$$D^{ri} = \eta/p_s; \quad D^{cpt} = 1/p_s^{cpt} + (\eta - 1). \tag{7}$$

D. Packet Reliability Ratio

The reliability of a packet transmission in this study refers to its successful transmission without collision. We measure this reliability in terms of the number of collisions encountered by a node in order to transmit η packets successfully. The fewer the collisions, the higher the reliability. Accordingly, we define packet reliability ratio as the number of packets delivered successfully per collision. For RI-WuR, the number of slots having collisions is $n_f^{ri} = (\eta/p_s) \cdot p_f$, where $p_f = p_{sf} - p_s$. For RI-CPT-WuR, it is $n_f^{cpt} = (1/p_s^{cpt}) \cdot p_f^{cpt}$. Correspondingly, the packet reliability ratios per node for each protocol are given respectively by

$$\gamma^{ri} = 1/n_f^{ri}; \quad \gamma^{cpt} = \eta/n_f^{cpt}. \tag{8}$$

E. Energy Analysis

To calculate the average energy consumed in a slot, we consider the following energy consumption components associated with the RN during: i) a successful transmission when it contends with other k nodes $E_s = t_{DATA} \cdot P_{tx}^{mr} + (T_{slot} - t_{DATA}) \cdot P_{rx}^{mr}$; ii) a transmission failure (collision) $E_f = t_{DATA} \cdot P_{tx}^{mr} + (T_{slot} - t_{DATA}) \cdot P_{rx}^{mr}$; iii) overhearing $E_{oh} = T_{slot} \cdot P_{rx}^{mr}$; and iv) the inactive period $E_{ina} = T_{slot} \cdot P_{sl}^{mr}$; where T_{slot}, t_{DATA} are the corresponding slot and packet transmission times and $P_{tx}^{wur/mr}$, $P_{rx}^{wur/mr}$, and $P_{sl}^{wur/mr}$ are the transmission, reception, and sleep power levels respectively of the WuR or MR. Note that among these energy consumption components we have $E_s = E_f$. The reason is as follows. In RI-CPT-WuR, a beacon message sent by the sink is always required after each DATA frame transmission. No matter it indicates the ongoing DATA transmission as successful or failed, the sending node needs to decode the beacon message, thus consuming the same amount of energy.

In a slot, when the RN is active, a successful transmission can occur with a probability p_s or a collision may happen with a probability p_f. If the RN is inactive, it will sleep. Consider that a cycle contains n slots. Obviously, these n slots include slots with a successful transmission and failed transmission due to collision as well as the slots in which the RN sleeps. It is clear that the energy consumed by the RN in a cycle includes all the energy consumptions during these mentioned slots.

For the RI-WuR operation, the number of successful slots is given by $n_s^{ri} = \eta$ and the number of slots in which a collision happened is $n_f^{ri} = (\eta/p_s) \cdot p_f$. Similarly, the number of successful slots where the RN lost the competition can be calculated as $n_l^{ri} = (\eta/p_s) \cdot (1 - p_{sf})$, where $p_{sf} = p_s + p_f$. Therefore, the energy consumed by the RN in RI-WuR during an *active* period of a cycle is given by,

$$\begin{aligned} E_{active}^{ri} = (&n_s^{ri} \cdot E_s + n_f^{ri} \cdot E_f + t_{WuC} \cdot P_{rx}^{wur}) \\ &+ n_l^{ri} \cdot E_{oh} + (n - (n_s^{ri} + n_f^{ri} + n_l^{ri})) \cdot E_{ina}. \end{aligned} \tag{9}$$

For the RI-CPT-WuR operation, the number of successful slots is given by $n_s^{cpt} = \eta$ and the number of slots in which a collision happened is $n_f^{cpt} = (1/p_s^{cpt}) \cdot p_f^{cpt}$. Similarly, the number of successful slots where the RN lost competition can be calculated as $n_l^{cpt} = (1/p_s^{cpt}) \cdot (1 - p_{sf}^{cpt})$. The energy consumed by the RN in RI-CPT-WuR during an *active* period of a cycle, E_{active}^{cpt} can be calculated by replacing n_s^{ri}, n_f^{ri}, and n_l^{ri} values with n_s^{cpt}, n_f^{cpt}, and n_l^{cpt} in (9). Therefore, the energy consumed by the RN during a *sleep* period of a cycle is given, in both RI-WuR and RI-CPT-WuR, by,

$$\begin{aligned} E_{sleep} = &((n \cdot T_{slot})) \cdot P_{sl}^{wur} \\ &+ (T - (n \cdot T_{slot}) - t_{WuC}) \cdot (P_{rx}^{wur} + P_{sl}^{mr}). \end{aligned} \tag{10}$$

Then, the energy consumption in a cycle for each protocol is obtained by,

$$E = E_{active} + E_{sleep}. \tag{11}$$

Correspondingly, the lifetime of the RN is determined as,

$$LT = E_{initial}/E. \tag{12}$$

Finally, the energy efficiency of the RN is obtained as,

$$\xi = \eta/E. \tag{13}$$

F. Performance Analysis When Channel Is Not Error-Free

Packet error rate (PER) is an important performance parameter representing the ratio between the number of failed transmissions and the total number of transmissions. Generally, interference, noise and channel fading are the predominant factors that cause errors during packet transmissions. These factors can be characterized by signal-to-noise ratio or signal-to-interference-noise ratio. While many prior studies concentrated on bit error rate (BER) [25]–[27], some recent papers have also considered packet or frame error rate [28]–[30].

In RI-CPT-WuR, a cycle starts from the successful transmission of a WuC frame, as shown in Fig. 3. Denote by N_a the number of active nodes and by q_i the queue length for active node i. In a cycle, there are $\beta = \sum_{i=1}^{N_a} q_i$ number of DATA packets to be transmitted including q_i packets from each active node and a beacon message, i.e., B, that is required after each DATA transmission. Accordingly, the PER for a whole cycle, denoted by P_{ep}^{cpt}, can be calculated as

$$P_{ep}^{cpt} = 1 - (1 - P_e^{WuC}) \cdot \prod_{j=1}^{\beta} [(1 - P_e^{DATA_j}) \cdot (1 - P_e^{B_j})] \quad (14)$$

where P_e^{WuC}, $P_e^{DATA_j}$, and $P_e^{B_j}$ are the PER of the WuC, the j^{th} DATA frame, and its corresponding beacon frame due to channel impairment respectively. To obtain each of these PER values, the generic relationship between BER, P_b, and PER, P_e, applies, as $P_e = 1 - (1 - P_b)^{frame\_length}$.

Note that P_{ep}^{cpt} represents the fraction of failed packet transmissions due to channel impairments and it is different from P_f^{cpt} which is caused by collisions. While P_f^{cpt} happens *during* a channel access competition, P_{ep}^{cpt} is the consequence of channel impairment *after* a node has obtained channel access. Therefore, when the RI-CPT-WuR MAC protocol is operating under an error-prone channel, both P_{ep}^{cpt} and P_f^{cpt} need to be considered in performance analysis.

Denote by ρ_s^{cpt} the probability of having a successful packet transmission in an error-prone channel. From the above discussion, it is obtained by

$$\rho_s^{cpt} = (1 - P_{ep}^{cpt}) \cdot P_s^{cpt}, \quad (15)$$

where P_s^{cpt} is the probability of a successful transmission under an error-free channel obtained in Section IV. Clearly, a packet is successfully transmitted only when no channel error happened during the transmission even through the channel is error-prone. Similarly, the probability of a packet transmission in the error-prone environment, ρ_{sf}^{cpt}, is obtained as

$$\begin{aligned}\rho_{sf}^{cpt} &= (1 - P_{ep}^{cpt}) \cdot P_s^{cpt} + P_{ep}^{cpt} \cdot P_s^{cpt} \\ &\quad + (1 - P_{ep}^{cpt}) \cdot P_f^{cpt} + P_{ep}^{cpt} \cdot P_f^{cpt} = P_s^{cpt} + P_f^{cpt}. \quad (16)\end{aligned}$$

Correspondingly, the probability of a failed transmission under error-prone conditions, considering both collisions and channel failures, ρ_f^{cpt}, is obtained by

$$\rho_f^{cpt} = P_f^{cpt} + P_{ep}^{cpt} \cdot P_s^{cpt}. \quad (17)$$

By replacing P_{sf}^{cpt}, P_s^{cpt}, and P_f^{cpt} with ρ_{sf}^{cpt}, ρ_s^{cpt}, and ρ_f^{cpt} respectively, the performance metrics under an error-prone channel condition can be obtained in the same way as shown earlier in this section for an error-free channel.

TABLE VI
THE CONFIGURED NETWORK PARAMETERS [10], [11], [21]

$N \in (1, 2 \ldots, 10)$	$Q \in (1, 2 \ldots, 10)$	$\lambda = 0.5$ packet/s
$WuC = 12.2$ ms	$B = 6$ bytes	$S = 100$ bytes
$P_{tx}^{mr} = 52.2$ mW	$P_{rx}^{mr} = 56.4$ mW	$P_{sl}^{mr} = 0.3$ μW
$P_{rx}^{wur} = 0.024$ mW	$P_{sl}^{wur} = 0.0035$ mW	$DR = 250$ kbps

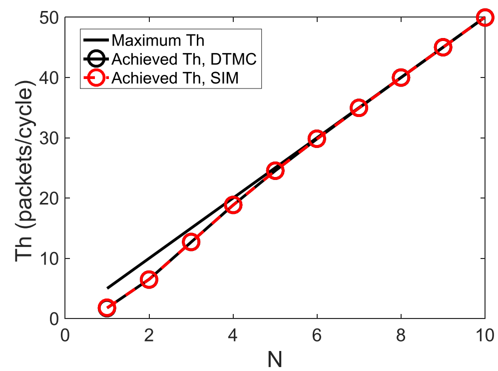

Fig. 4. Throughput with different N.

VI. SIMULATIONS AND NUMERICAL RESULTS

In this section, we validate the proposed models by comparing the derived metrics from the models with the results obtained through discrete-event simulations. Both the RI-WuR and RI-CPT-WuR MAC protocols are simulated in a custom-built simulator using the simulation and modeling programming language (SMPL) [36], [37]. The metric values per cycle reported in this section are the average values calculated over $5 \cdot 10^6$ cycles. The configured network parameters are listed in Table VI, where S is the packet size and DR is the transmission data rate of the MR.

Recall that the cycle length of a receiver-initiated MAC protocol is variable according to the number of slots. The configurable number of competing slots in a cycle depends directly on the number of nodes and the queue size, meaning that the duration of a cycle depends on both N and Q. Accordingly, the protocols are evaluated based on the following two configurations: 1) by varying the number of nodes N with a fixed Q at 5 packets; and 2) by varying the maximum queue capacity Q with $N = 5$, first under error-free channel conditions and then for error-prone channels. To obtain the numerical results presented below, all nodes behave homogeneously according to the adopted MAC protocol, with the same initial energy level as $E_{initial} = 1$ J.

A. Performance Comparison With Variable Number of Nodes

From the protocol principle of RI-CPT-WuR, it is clear that one of the essential operations is to complete the transmissions of all packets in the queue by all nodes in a cycle, regardless of queue length. Obviously, the same throughput is achieved by both RI-CPT and RI-WuR protocols as shown in Fig. 4. However, the other performance parameters are protocol specific. The cycle duration is shorter for a lower N and when few packets arrive at nodes and vice versa. Fig. 4 depicts the network throughput for different number of nodes in the network at a fixed $Q = 5$ packets. As shown in the figure,

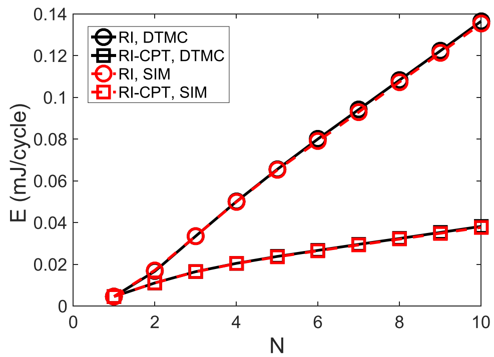

Fig. 5. Energy consumption with different N.

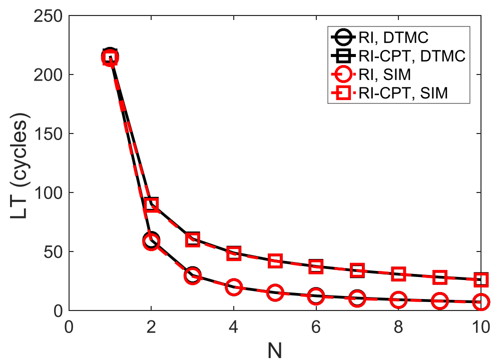

Fig. 6. Lifetime with different N.

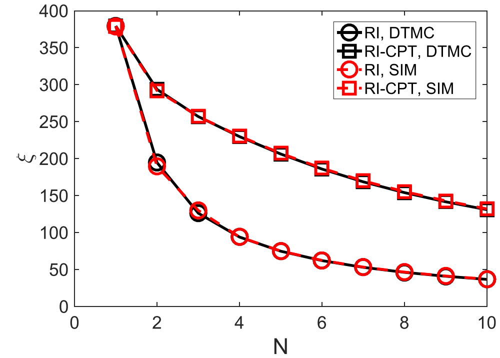

Fig. 7. Energy efficiency with different N.

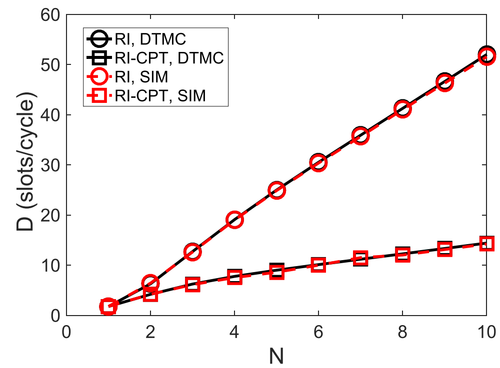

Fig. 8. Delay with different N.

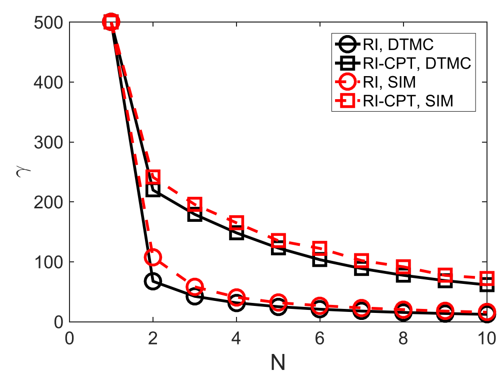

Fig. 9. Packet reliability ratio with different N.

up to $N = 4$, when few packets arrive at nodes the number of packets accumulated in a cycle is not enough to achieve the maximum throughput. Since the maximum queue length is configured as $Q = 5$, each node should contain 5 packets in its queue in order to reach the achievable maximum throughput of $\eta = 5$. With $N = 5$, the cycle duration is sufficient to accumulate 5 packets in the queue of each node, thus achieving the maximum node throughput. It can be observed that the increase in N attains higher Th and the throughput curve moves toward the maximal point.

As mentioned earlier, the higher the number of nodes, the larger the number of slots in a cycle. Accordingly, the energy consumed by the RN is higher in RI-WuR since it overhears the packets from the winning node in all slots. Even in case of collisions, all nodes overhear. As a result, E consumed in RI-WuR increases linearly with the congestion status in the network. On the other hand, RI-CPT-WuR substantially reduces energy consumption by confining overhearing to merely one slot. Therefore, lower energy is consumed in RI-CPT-WuR when compared with RI-WuR, as shown in Fig. 5. Correspondingly, the lifetime of the RN is longer in RI-CPT-WuR. Moreover, the energy efficiency is also higher with RI-CPT-WuR due to the transmission of η packets per cycle with lower energy consumption per cycle than the ξ of RI-WuR which transmits the same number of packets but with higher E. In a nutshell, even though both LT and ξ decay with a higher competition, RI-CPT-WuR enhances the performance of these parameters by almost four times as acquired by RI-WuR at $N = 10$, as shown in Figs. 6 and 7 respectively.

Similarly, the average number of slots required for transmitting all packets in a cycle is lower with the RI-CPT-WuR MAC protocol since it needs fewer competitions in a cycle, as shown in Fig. 8. With a lower number of competitions, the resulted delay with RI-CPT-WuR MAC is shorter by the factor of Q. For the same reason, the number of collisions which take place in RI-CPT-WuR is lower and the packet reliability ratio is higher when compared with RI-WuR, as depicted in Fig. 9. This result can easily be explained by the fact that RI-CPT-WuR delivers η packets with a fewer number of collisions where as RI-WuR delivers the same number of packets with a higher number of collisions. For packet reliability ratio, γ decreases with the node density in the network as p_s reduces, RI-CPT-WuR achieves four times higher γ than the one gained by RI-WuR at $N = 10$.

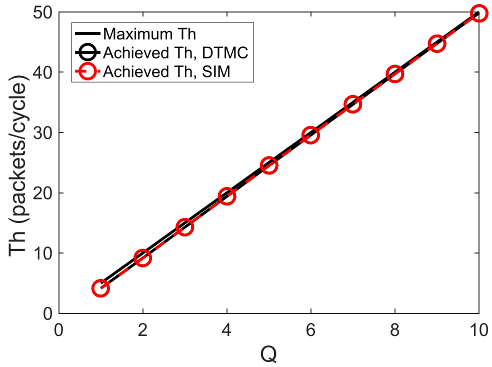

Fig. 10. Throughput with different Q.

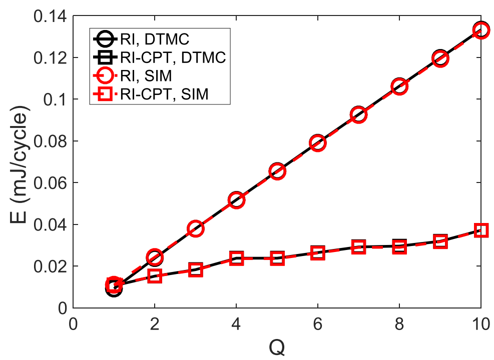

Fig. 11. Energy consumption with variable Q.

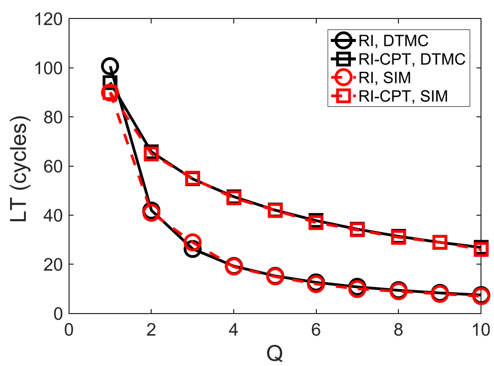

Fig. 12. Lifetime with different Q.

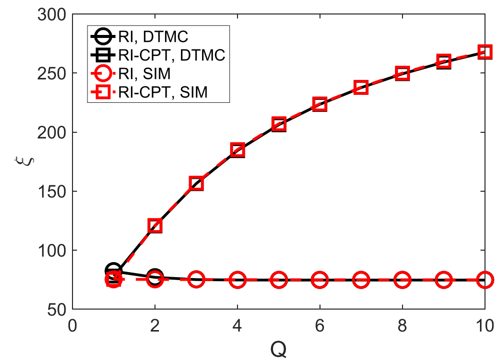

Fig. 13. Energy efficiency with different Q.

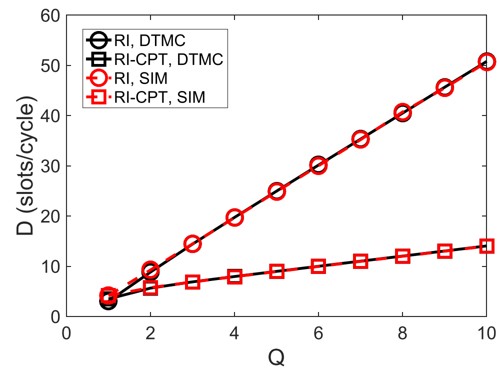

Fig. 14. Delay with different Q.

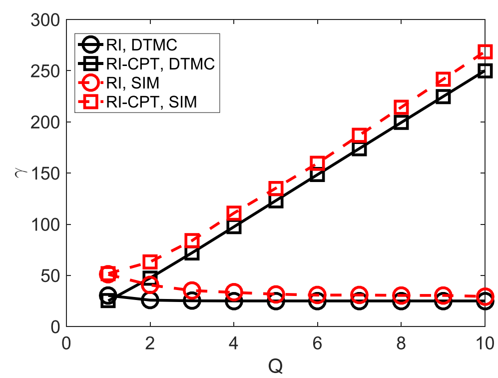

Fig. 15. Packet reliability ratio as Q varies.

B. Performance Comparison With Variable Queue Capacity

As expected, the duration of cycles is longer with a larger Q and higher throughput is achieved when more packets are generated in the network. Fig. 10 depicts the network throughput with different queue sizes for both protocols. At $N = 5$, Th reaches its maximum even at $Q = 1$ and maintains the same for all Q values. Consequently E increases linearly, resulting a shorter lifetime with a larger Q in RI-WuR. In contrast, overhearing is confined in RI-CPT-WuR. So lower energy is consumed and consequently it operates the network for a longer lifetime as presented in Figs. 11 and 12. Moreover, the energy efficiency of RI-CPT-WuR is increased significantly and it gains almost four times higher than the one obtained by RI-WuR at $Q = 10$, as shown in Fig. 13. The reason for this result is the linear increment in η with slowly increasing energy consumption. However, the energy efficiency of RI-WuR remains almost stable across different queue capacities with linear increments at the same rate for both η and E.

As illustrated in Fig. 14, the delay per cycle is longer in RI-WuR with a larger queue size as it needs to compete in more slots. On the other hand, the achieved delay with the RI-CPT-WuR MAC protocol is much shorter and it is almost stable. This is because of the fact that the number of competitions is directly corresponding to N which is fixed as 5. For the same reason, n_f^{cpt} is lower and its packet reliability ratio is increased linearly with Q, as depicted in Fig. 15. This is the result of the fact that RI-CPT-WuR delivers η ($\approx Q$) packets with a fewer number of collisions, gaining Q times higher γ than that of RI-WuR at $Q = 10$.

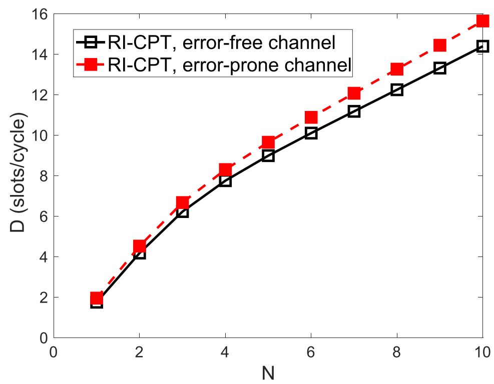

Fig. 16. Delay with/without channel errors.

C. Performance Comparison Under an Error-Prone Channel

To evaluate the performance of RI-CPT-WuR under error-prone channel conditions, we conducted simulations based on a network with a varying number of nodes $N = 1 \sim 10$, each with $Q = 5$, $\lambda = 0.5$ packet/s, and it is operated under an error-prone channel with $P_{ep}^{cpt} = 0.1$. In Figs. 16 to 18, we illustrate the performance in terms of delay, lifetime, and energy efficiency and compare the results with the ones obtained under an error-free channel.

In an extreme case when there is only one active node, that node will deliver its q packets consecutively after receiving a WuC. Even though some transmissions failed due to channel errors, those packets with failed transmissions will be retransmitted immediately. Therefore, the delay resulted in the error-prone channel is slightly longer than the one obtained in the error-free channel. However, access competition exists as more number of nodes become active. Recall that RI-CPT-WuR reserves slots as many as the number of packets nodes contain. Because of channel errors, some packets may have to be retransmitted. In that case, a packet with failed transmission is retransmitted in the next slot. The same procedure repeats for each packet in the queue until all reserved slots are utilized. When transmission failures occur, a node needs to compete again for transmitting its remaining packets by requiring additional slots, resulting in a longer delay. Therefore, the delay difference is larger when there are more active nodes in the network, as depicted in Fig. 16. At $N = 10$, on average 1.25 additional slot is required to transfer the same number of packets when $P_{ep}^{cpt} = 0.1$.

Moreover, the larger the node population, the higher the access competition. Consequently, each node consumes higher energy in an error-prone channel, leading to a shorter lifetime, as shown in Fig. 17. For the same reason, lower energy efficiency is observed in Fig. 18 when more retransmissions are required due to channel failures. Note however that the same network throughput is achieved under both channel conditions. This is because throughput in this paper is defined as the total number of packets delivered in the same cycle *regardless of the number slots used in that cycle*. In this case, the difference between these two channel conditions exists only in terms of energy consumption and energy efficiency. For a network with $N = 10$ nodes and the same configuration for other parameters, a 10% error-prone channel causes on average 8.4% lower energy efficiency.

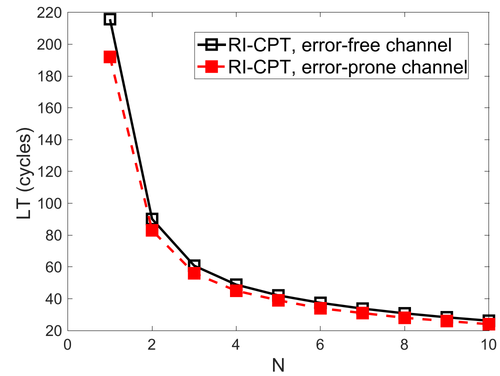

Fig. 17. Lifetime with/without channel errors.

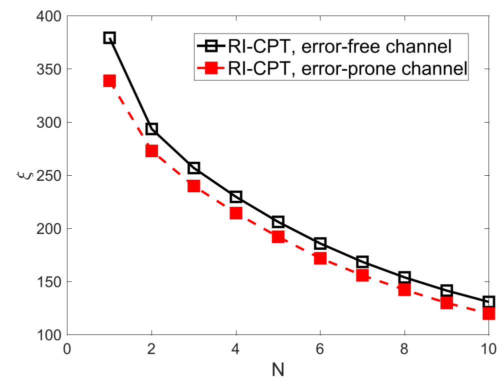

Fig. 18. Energy efficiency with/without errors.

VII. Conclusions

In this paper, we proposed a novel receiver-initiated WuR MAC protocol in order to improve delay, packet reliability ratio, and energy efficiency for WuR enabled IoT networks. The proposed RI-CPT-WuR MAC protocol allows nodes transmit multiple packets consecutively with one successful access competition and its parameters are configurable based on traffic arrival rate, network population, as well as queue size. Moreover, we developed two DTMC models to evaluate the performance of the RI-CPT-WuR MAC and RI-WuR protocols. By jointly solving these two DTMCs, the successful transmission probability is calculated. We further deduced expressions for performance metrics including node and network throughput, delay, packet reliability ratio, energy consumption and lifetime, as well as energy efficiency. The obtained numerical results based on both error-free and error-prone channel conditions demonstrate that the RI-CPT-WuR protocol outperforms the prevailing RI-WuR protocol with respect to all these studied parameters. The discrete-event simulation results confirm that the operation of both RI-CPT-WuR and RI-WuR protocols can be precisely predicted based on the developed models.

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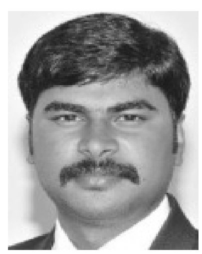

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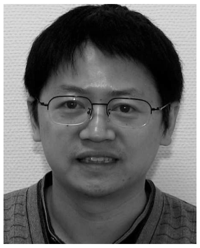

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