Performance Analysis of IEEE 802.15.4 with Non-Beacon-enabled CSMA/CA in Non-Saturated Condition

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Abstract. This paper proposes an analytical model of IEEE 802.15.4, which is a standard toward low complexity, low power consumption and low data rate wireless data connectivity. In this paper, we concentrate on the MAC performance of the IEEE 802.15.4 LR-WPAN in a star topology with unslotted CSMA/CA channel access mechanism under non-saturated modes. Our approach is to model stochastic behavior of one device as a discrete time Markov chain model. We believe that many WSN applications would benefit from our analytical model because many applications in WSN generate traffic in non-saturated mode. We obtain five performance measures : throughput, packet delay, number of backoff, energy consumption and packet loss probability. Our results are used to find optimal number of devices satisfying some QoS requirements.

1 Introduction

Recently, there has been a significant increase in research of wireless sensor networks (WSN). Network communication requirement of WSN is different from that of the traditional network because the traditional performance criteria of network are throughput, latency, and fairness, whereas in WSN, energy efficiency becomes more important. Making a system energy efficient in WSN is a challenging research topic and researchers have developed many algorithms [1–3].

Many researchers have concentrated on the Medium Access Layer (MAC) in WSN since traditional wireless MAC such as IEEE 802.11 is not energy efficient. However, developing mathematical model of energy efficient MAC has not been

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thoroughly studied. This is important because we can analyze and expect system behavior by simply applying various parameters into applications in WSN.

In this paper, we propose an analytical model of IEEE 802.15.4 which is standardized toward low complexity, low power consumption and low data rate wireless data connectivity. This standard allows two network topologies: star and peer-to-peer. In a star topology, every sensors must communicate through PAN coordinator. In a peer-to-peer topology all devices can communicate each other if both devices are within a physical range. In a star topology, network uses two types of network channel access mechanism. One is based on the slotted CSMA/CA in which slots are aligned with the beacon enabled. Another access mechanism is based on the unslotted CSMA/CA without beacon frame.

This paper concentrates on the MAC performance of the IEEE 802.15.4 network with star shaped non-beacon mode and unslotted CSMA/CA channel access mechanism under non-saturated modes. We believe that many WSN applications such as [4] would benefit from this analytical model. Our approach is to model the stochastic behavior of one device as a discrete time Markov chain model. Our Markov chain model of IEEE 802.15.4 is different from one of IEEE 802.11 [5], since no freezing of backoff counter operates during transmission of other devices and two CCA are needed in IEEE 802.15.4. Park et al. [6] also proposed analysis on 802.15.4 but they focused on saturated mode where devices have always packets to send.

In this paper, we investigate MAC performance of the IEEE 802.15.4 in non-saturated mode, where the arrival process of packets to device follows Bernoulli process with low rate, so device does not have packets to send quite often. In fact, most of real applications of LR-WPAN operate in non-saturated mode so that our analytical model will be applicable to wide range of WSN. We obtain five performance measures : throughput, packet delay, number of backoff, energy consumption and packet loss probability. Our results are used to find optimal number of devices with some constraints on these measures.

This paper is organized as follows. Section 2 proposes our analytical model of 802.15.4 in a non-saturated mode. Section 3 obtains performance measures developed from our analysis. In Section 4, parameters of non-saturated modes are explained. Section 4.1 presents numerical results of the heavy case and section 4.2 presents the light case. Section 5 concludes the paper and suggests future work.

2 Analytical model

In order to analyze MAC performance of the IEEE 802.15.4 LR-WPAN with non-beacon mode and unslotted CSMA/CA channel access mechanism, we introduce a discrete time Markov chain model for activity of a sensor device under non-saturation modes, as shown in Fig. 1. Let n sensor devices be associated with the network coordinator. We assume that a sensor device can have only one packet at a time so that if the sensor device has a packet to transmit then no other packet is created. This assumption is reasonable because a packet's arrival occurs infrequently and the service time is rather short in the practical applications. We assume that the arrival of each packet in idle state follows a Bernoulli process with probability P_{idle}. We assume that the length of a packet measured in slots is geometrically distributed with mean $\frac{1}{1-P_{\text{Tx}}}$ and the MAC sublayer will retry the transmission of the packet until positive acknowledgment is received.

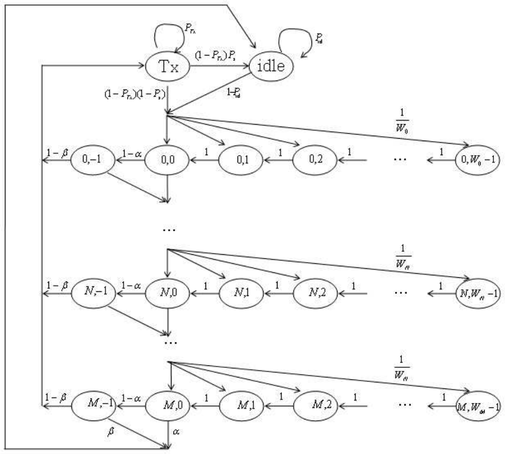

Fig. 1. Diagram of one-step transition probabilities

Let $s(t)$ represent the number of backoff (NB) at time t (In contrast to models for IEEE 802.11 WLAN, t corresponds directly to system time.); $0 \leq s(t) \leq M$ where M is $macMaxCSMABackoffs - 1$. Let $b(t)$ be the backoff counter or transmission counter of the sensor device. Let us adopt the notation $W_j = 2^j W_0$ for $j \leq N$ and $W_j = W_N$ for $j > N$, where $W_0 = 2^{BE_{min}}$. The backoff counter is decremented to zero and then two CCA's are performed. The value $b(t) = -1$ corresponds to the situation that the channel is idle at the first CCA. The **Tx** state represents the state of packet transmission which includes the duration for waiting and receiving ACK. The **idle** state represents the state in which the sensor device does not have any packet to transmit. Define $X(t)$ by

$$X(t) = \begin{cases} (s(t), b(t)), & \text{when a device is in the process of backoff steps} \\ \textbf{Tx}, & \text{when a device is in the process of packet transmission} \\ \textbf{idle}, & \text{when a device is in the idle state} \end{cases}$$

at t. Then $X(t)$ is a discrete Markov chain with one-step transition probabilities described in Fig. 1. Let $\pi_{i,j}$, π_{Tx} and π_{idle} be the steady-state probabilities for this Markov chain. The key assumption for this Markov chain model is that the busy probabilities of the channel at the first CCA(CCA^1) and the second CCA(CCA^2) are α and β, respectively, regardless of the stages.

Next we will express the probabilities α and β and the successful transmission probability P_s in terms of $\pi_{i,j}$, π_{Tx} and π_{idle}. Since the idle probability $1-\alpha$ of the channel at CCA^1 of the given device is equal to the probability that all other $n-1$ sensor devices are in the states except the transmission state **Tx**, α can be given by :

$$\alpha \ = \ 1-(1-\pi_{\mathrm{Tx}})^{n-1} \tag{1}$$

To determine β we observe that the preceding slot must be idle. So β is the probability that the medium is busy when the tagged device does its CCA^2, given that the medium was idle during its CCA^1,

$$\begin{aligned}\beta &= P\{\text{the channel is busy at CCA}^2 \mid \text{the channel is idle at CCA}^1\} \\ &= \frac{P\{\text{the channel is idle at CCA}^1\text{, the channel is busy at CCA}^2\}}{P\{\text{the channel is idle at CCA}^1\}} \\ &= \frac{(1-\pi_{\mathrm{Tx}})^{n-1} - (1-\pi_{\mathrm{Tx}} - \sum_{i=0}^{M} \pi_{i,-1})^{n-1}}{1-\alpha} \end{aligned} \tag{2}$$

The successful transmission probability, P_s, is calculated by

$$\begin{aligned} P_s &= P\{\text{successful transmission} \mid \text{the channel is idle at CCA}^1 \text{ and CCA}^2\} \\ &= \frac{\{1-\pi_{\mathrm{Tx}} - \sum_{i=0}^{M}(\pi_{i,0}+\pi_{i,-1})\}^{n-1}}{(1-\pi_{\mathrm{Tx}} - \sum_{i=0}^{M}\pi_{i,-1})^{n-1}} \end{aligned} \tag{3}$$

The steady-state probabilities for the Markov chain, $\pi_{i,j}$, π_{Tx} and π_{idle}, are represented as follows.

$$\begin{cases} \pi_{i,0} = (\alpha+\beta-\alpha\beta)^i \pi_{0,0} \quad \text{if } 1 \le i \le M \\ \pi_{i,-1} = (1-\alpha)\pi_{i,0} \quad \text{if } 0 \le i \le M \\ \pi_{0,j} = \pi_{0,0} - \{(1-P_{\mathrm{Tx}})(1-P_s)\pi_{\mathrm{Tx}} + (1-P_{\mathrm{idle}}\pi_{\mathrm{idle}})\} \quad \text{if } 1 \le j \le W_0 - 1 \\ \pi_{i,j} = \pi_{i,0} - \frac{j}{W_i}(\alpha\pi_{i-1,0} + \beta\pi_{i-1,-1}) \quad \text{if } 1 \le i \le M,\ 1 \le j \le W_i - 1 \\ \pi_{\mathrm{Tx}} = \frac{1-\beta}{1-P_{\mathrm{Tx}}} \sum_{i=0}^{M} \pi_{i,-1} \\ \pi_{\mathrm{idle}} = \frac{1}{1-P_{\mathrm{idle}}}\{\alpha\pi_{M,0} + \beta\pi_{M,-1} + (1-P_{\mathrm{Tx}})P_s\pi_{\mathrm{Tx}}\} \end{cases} \tag{4}$$

All steady-state probabilities for this Markov chain can be represented in terms of $\pi_{0,0}$. Since expressions for α and β in (1) and (2) require the knowledge of steady-state probabilities, $\pi_{0,0}$ can be determined by solving a nonlinear coupled system of (1), (2) and the normalization condition from (4).

3 Performance measures

In this section, we obtain several performance measures to evaluate WSN such as throughput, delay, number of backoff, energy consumption and loss probability.

1. **Throughput:** the normalized system throughput S, defined as the fraction of time the channel is used to successfully transmit, is

$$S = \frac{n}{1-P_{\mathrm{Tx}}} \sum_{i=0}^{M} \pi_{i,0}(1-\alpha)(1-\beta)P_s \tag{5}$$

2. **Delay:** we calculate the average delay $\mathrm{E}(D)$ for a packet, where delay is the duration from the moment of packet arrival at device to service completion point.

$$
\begin{aligned}
\mathrm{E}(D) ={}& \sum_{v=0}^{M}\sum_{r=0}^{v} {}_v\mathrm{C}_r \alpha^r \{(1-\alpha)\beta\}^{v-r}(1-\alpha)(1-\beta)P_s \left(\sum_{i=0}^{v}\frac{W_i-1}{2}+2v-r\right. \\
&\left.+\frac{1}{1-P_{\mathrm{Tx}}}\right) + \sum_{v=0}^{M}\sum_{r=0}^{v} {}_v\mathrm{C}_r \alpha^r \{(1-\alpha)\beta\}^{v-r}(1-\alpha)(1-\beta)(1-P_s) \\
&\times \left(\sum_{i=0}^{v}\frac{W_i-1}{2}+2v-r+\frac{1}{1-P_{\mathrm{Tx}}}+\mathrm{E}(D)\right) + \sum_{r=0}^{M} {}_M\mathrm{C}_r \alpha^r \{(1-\alpha)\beta\}^{M-r} \\
&\times \left\{\alpha\left(\sum_{i=0}^{M}\frac{W_i-1}{2}+2M-r-2\right)+(1-\alpha)\beta\left(\sum_{i=0}^{M}\frac{W_i-1}{2}+2M-r-1\right)\right\}
\end{aligned} \tag{6}
$$

The first term and second term of the equation (6) describe the cases of successfully transmission and collision in first transmission, respectively. The last term of the equation (6) describes the case that the device can not attempt transmission because the channel is continuously sensed due to busy condition in CCA. After solving the system (4), we can obtain the average delay for a packet.

3. **Number of backoff:** the average number $\mathrm{E}(N_{\mathrm{backoff}})$ of backoff stages which a packet experience is

$$
\begin{aligned}
\mathrm{E}(N_{\mathrm{backoff}}) ={}& \sum_{v=0}^{M}\sum_{r=0}^{v} {}_v\mathrm{C}_r \alpha^r \{(1-\alpha)\beta\}^{v-r}(1-\alpha)(1-\beta)P_s(v+1) \\
&+\sum_{v=0}^{M}\sum_{r=0}^{v} {}_v\mathrm{C}_r \alpha^r \{(1-\alpha)\beta\}^{v-r}(1-\alpha)(1-\beta)(1-P_s)(v+1+\mathrm{E}(N_{\mathrm{backoff}})) \\
&+\sum_{r=0}^{M} {}_M\mathrm{C}_r \alpha^r \{(1-\alpha)\beta\}^{M-r}(M+1)
\end{aligned} \tag{7}
$$

4. **Energy consumption:** since power is quite critical in a sensor network, energy consumption is the most important performance measure. To obtain the total lifetime of a battery, we need a concept of average energy consumption. Park et al. [6] and Pollin et al. [7] define the normalized energy consumption as the average energy consumption to transmit one slot amount of payload. Their definition has good explanation in saturation mode. However, in non-saturation mode, their definition mismatches with our intuition, as they [7] mentioned that the energy consumption increases as the arrival rate decreases, or equivalently idle period increases. See Fig. 9 in [7]. So, we define the average energy consumption per one slot(mJ/slot), E^{slot} as total energy consumption during one cycle divided by the total number of

slots in one cycle. One cycle begins from the moment of beginning idle to the moment when the transmission of a packet is completed. Let E_{Tx}, E_{Rx}, E_{CCA} and E_{idle} be the energy consumption for transmission slot, receiving slot, CCA slot and idle slot. Then E^{slot} can be computed by

$$\begin{aligned} E^{\mathrm{slot}} = &\ \{1 - \sum_{i=0}^{M}(\pi_{i,0} + \pi_{i,-1}) - \pi_{\mathrm{Tx}}\}E_{\mathrm{idle}} + \sum_{i=0}^{M}(\pi_{i,0} + \pi_{i,-1})E_{\mathrm{CCA}} \\ &+\pi_{\mathrm{Tx}}\{(\frac{1}{1-P_{\mathrm{Tx}}} - T_{\mathrm{wait}-T_{\mathrm{ACK}}})E_{\mathrm{Tx}} + (T_{\mathrm{wait}} + T_{\mathrm{ACK}})E_{\mathrm{Rx}}\}(1 - P_{\mathrm{Tx}}) \end{aligned} \tag{8}$$

where T_{wait} and T_{ACK} are the time durations measured in slots waiting ACK and sending ACK, respectively. Our definition of E^{slot} matches with our intuition as shown in Section 4. It is easy to find lifetime of a battery as in (9). Let E^{battery} be the amount of energy for battery. Then the life time of battery, $L^{battary}$ is

$$L^{battary} = \frac{E^{\mathrm{battery}}}{E^{\mathrm{slot}}} \times \sigma \quad , \tag{9}$$

where σ is the length of a slot and $\sigma = 0.32$ms in case of 250 Mbps, 2.4 GHz.

5. **Loss probability:** the packet loss probability P_{loss} is computed by

$$\begin{aligned} P_{\mathrm{loss}} = &\sum_{v=0}^{M}\sum_{r=0}^{v} {}_{v}\mathrm{C}_{r}\alpha^{r}\{(1-\alpha)\beta\}^{v-r}(1-\alpha)(1-\beta)(1-P_s)P_{\mathrm{loss}} \\ &+\sum_{r=0}^{M} {}_{M}\mathrm{C}_{r}\alpha^{r}\{(1-\alpha)\beta\}^{M-r}\{\alpha + (1-\alpha)\beta\} \end{aligned} \tag{10}$$

4 Numerical Examples

In the sensor network, arrivals occur quite rare and we divide non-saturated mode into three cases : heavy if $P_{\mathrm{idle}} \leq 0.9$, moderate if $0.9 < P_{\mathrm{idle}} \leq 0.99$, and light if $0.99 < P_{\mathrm{idle}} \leq 1$. P_{T_x} is set to $\frac{9}{10}$ so that the average length of a packet is 6. N and M are 2 and 4, respectively. W_0 is set to $2^3 = 8$ in our experiment. Section 4.1 presents numerical results of the heavy case and Section 4.2 presents the light case.

4.1 Heavy Case ($P_{\mathrm{idle}} \leq 0.9$)

First, let us vary P_{idle} from 0.1 to 0.9 to observe overall changes of performances. Fig. 2 depicts values of parameters α, β, and P_s. Both α and β increase as the number of devices increases, while P_s decreases as we expected. Note that β is bounded by $\frac{1}{2}$ as asserted in ([7]).

Fig. 3 shows the energy consumption E^{slot}, packet loss probability P_{loss}, the delay $\mathrm{E}(D)$ and the average number $\mathrm{E}(N_{\mathrm{backoff}})$ of backoff stages needed to

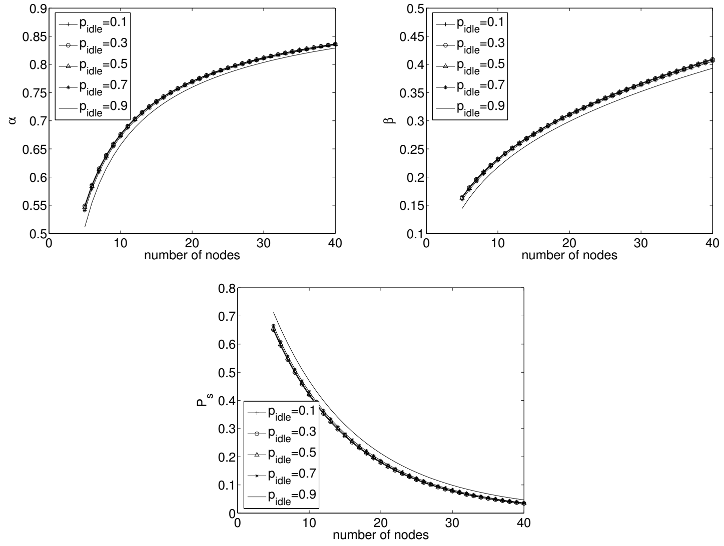

Fig. 2. Parameters for networks when P_{idle} ranges from 0.1 to 0.9

transmit the packet, when P_{idle} ranges from 0.1 to 0.9. The energy consumptions at T_x, R_x, and CCA states are 0.0100224mJ, 0.0113472mJ and 0.0113472mJ, respectively, [6]. A device consumes 0.000056736mJ during idle state. Both T_{wait} and T_{ACK} are set to 2. As the number of devices increases, devices will compete more with other devices to transfer, which is validated by decrease of throughput and increase of delay as illustrated in Fig. 3. As the number of devices increases, more devices find the channel busy and go to higher backoff stages so that the energy consumption decreases and P_{loss} increases. Note that when the number of devices exceeds 20, lots of packets are dropped (large P_{loss}) and the delay is slightly reduced.

Figure 4 shows the energy consumption of a node (Left) and the lifetime (Right) when the packet size increases from 2 to 26. We assumed that a battery used in each device has a capacity of 560 mAh at 3.0V. As the packet size increases, the energy consumption increases and the lifetime decreases, which is consistent with the intuition. Similar results are observed in [4].

4.2 Light Case ($P_{\text{idle}} \geq 0.99$)

Now let us consider a very light traffic whose P_{idle} values are greater than 0.99. In fact, packet arrivals are quite rare in many applications of the sensor network such as body area networks. Thus, it is quite reasonable to consider light traffic sensor network. P_{idle} in this simulation changes from 0.995 to 0.999. Fig. 5 depicts values of α, β, and P_s. α and β increase and P_s decreases as the number of nodes increases.

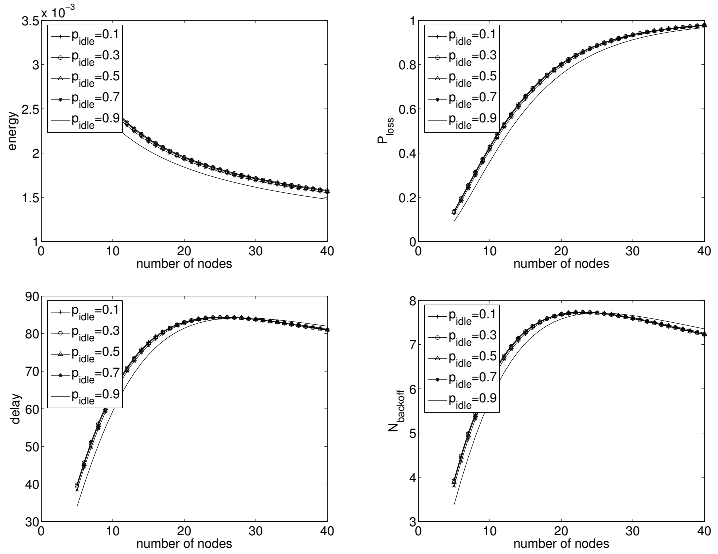

Fig. 3. Results for networks when P_{idle} ranges from 0.1 to 0.9

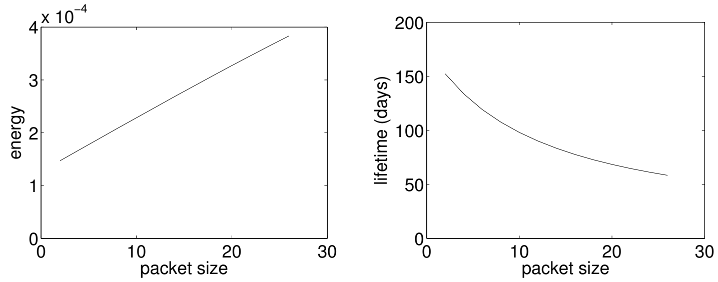

Fig. 4. Energy consumption and lifetime when the packet size increases from 2 to 26

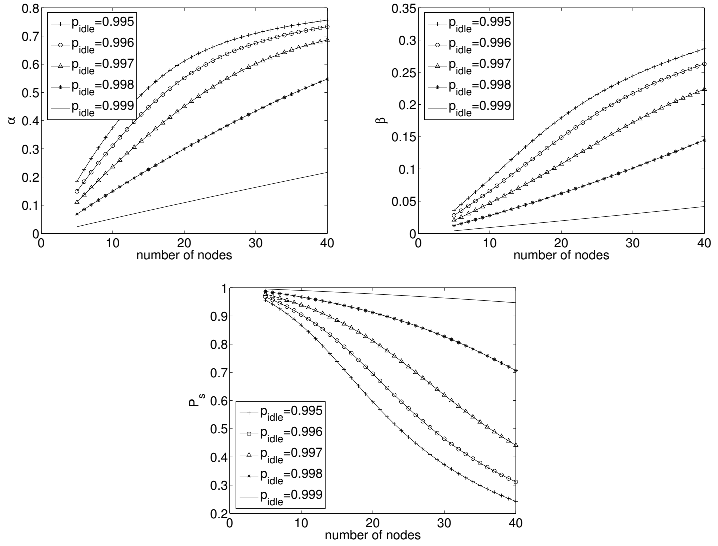

Fig. 5. Parameters for non-saturated networks when $P_{\rm idle}$ is near 1

Fig. 6 depicts the energy consumption, the packet loss probability, the delay and the number of backoff stages to experience. As the number of nodes increases, the delay increases as in heavy case. For a fixed $P_{\rm idle}$, negligible changes are observed in the energy consumption with respect to the number of devices. Since the packet arrival is rare, the energy consumption does not depend on the number of devices. Note that $P_{\rm loss}$ decreases dramatically and the probability is almost zero when the packet arrival event is extremely rare. Optimal values of parameters can be chosen depending on the needs of each application. For example, it is reasonable to assume $P_{\rm loss} \leq 20\%$ and delay $\leq 50ms$ in the body area network. Thus, when $P_{\rm idle}$ is 0.996, if the energy constraint is 0.8×10^{-3}, the optimal number of devices in the network is 20.

5 Conclusion and Future Work

In this work, we propose an analytical model of IEEE 802.15.4. We concentrate on the MAC performance of the IEEE 802.15.4 network with star shaped non-beacon mode and unslotted CSMA/CA channel access mechanism under non-saturated mode. Our approach is to model stochastic behavior of one device as a discrete time Markov chain model and we believe that many WSN applications would benefit from our analytical model because many applications in WSN generate traffic in non-saturated mode. We obtain five performance measures: throughput, packet delay, number of backoff, energy consumption and packet loss probability. Our results are used to find optimal number of devices with

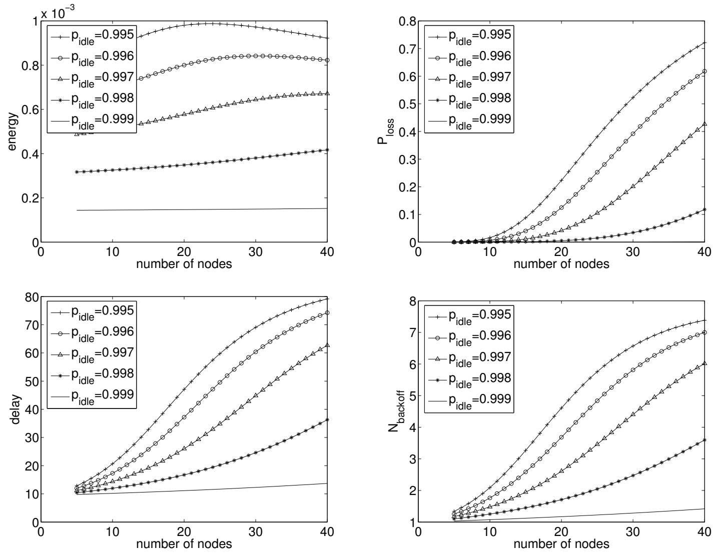

Fig. 6. Results for non-saturated networks when P_{idle} is near 1

some constraints on these measures. For example, in a body area network, with the constraint of $P_{\text{loss}} \leq 20\%$ and delay $\leq$ 50ms, when P_{idle} is 0.996 and the energy constraint is 0.8×10^{-3}, the optimal number of devices in the network is 20. Our study in this paper is limited to upload traffic. The performance analysis considering download traffic as well as upload traffic and validation with ns-2 are in progress.

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