Impacts of Network Parameters on Data Collection in Duty-cycled Wireless Sensor Networks

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Abstract. In wireless sensor works (WSNs), data collection is the most important evaluating criterion as well as network lifetime. This paper proposes a novel approach to investigate the most easily adjustable factors, these factors have an influence on network data collection both in coordinated and randomized duty-cycled sleep schedule networks. By analyzing and calculating the energy consumption, expected network lifetime and three major parameters are recognized as the indexes for evaluating the data collection. In addition, since most current WSNs adopt coordinated duty-cycled sleep schedule to reduce energy consumption and prolong network lifetime, we put forward a method to find the most optimal network parameters to guarantee the superiority of this kind of sleep schedule. We choose Connected k-Neighborhood (CKN) as the model of the coordinated sleep schedule. Simulation results show the most optimal network parameters can be found under expected network lifetime.

Keywords: WSNs, network parameters, duty-cycled.

1 Introduction

Recent technological advances have enabled the emergence of tiny, battery-powered sensors with limited on-board signal processing and wireless communication capabilities. WSNs may be deployed for a wide variety of applications [1]. In many applications of WSNs, the amount of data collection is critically essential, it can help to provide more information about real-time environment to a base station, thus help the base station make a proper decision. There are too many factors in WSNs that have impacts on data collection. These factors are inspired from the sensor nodes characteristics (nodes' limited power and cache capacity, etc.), the physical deployment of the WSNs (node density, sleep schedule and nodes' transmission radius, etc.), and the WSNs' information functions

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(transmission power, the signal to noise ratio and the radio coverage, etc.). In addition, network lifetime is another key factor of WSNs [2].

It is well known that node power is precious, therefore improving energy efficiency is critical to WSNs. Hence, many research has been done for duty-cycled sleep schedule to save energy. Duty-cycled mechanism can be classified into two basic categories: 1) $Randomized\ duty{-}cycled\ sleep\ schedule$, individual sensor node performs sleeping and waking up operations independently without checking their neighbor nodes' current status, 2) $Coordinated\ duty - cycled\ sleep\ schedule$, each sensor node performs sleeping and waking up operations according to their neighbor nodes' current status. The major difference between randomized duty-cycled sleep schedule WSNs and coordinated duty-cycle sleep schedule WSNs is the time-varying network connectivity: 1) In randomized duty-cycled WSNs, the network-wide connectivity is not guaranteed, 2) In coordinated duty-cycled WSNs, the network-wide connectivity is guaranteed.

In this paper, we assume nodes in WSNs operating with Connected k-Neighborhood (CKN) based sleep scheduling [3]. Compared to Randomized Sleep (RS) schedule [4], CKN algorithm is more energy balanced and energy consumption is lesser during the same network lifetime. We further investigate the most important and easily regulated network parameters in RS networks and CKN networks, respectively. Based on the results of extensive calculation and simulations, we can find the most superior parameters in CKN based networks to gain the most data collection.

The rest of this paper is organized as follows. In the next section, we summarize the related work, Section 3 we describe our method in details. The simulation along with results is done in Section 4. Finally, the paper is concluded in Section 5.

2 Related Work

2.1 Duty-Cycled Sleep Schedule

Duty-cycled sleep schedule has become a critical mechanism to minimize the energy consumption in WSNs. The basic idea of this mechanism is to put a part of sensor nodes in a low power sleep state instead of idle state. Previous literatures have proposed various duty-cycled sleep schedule for WSNs. In [5], Michael et al. present a low power MAC protocol X-MAC. X-MAC proposes solutions to problems like high energy consumption, excess energy consumption at nontarget receivers by employing a shortened preamble approach that retains the advantages of low power listening, namely low power communication, simplicity and a decoupling of transmitter and receiver sleep schedules.

Ghadimi et al. introduce a novel opportunistic routing metric that takes duty-cycled into account[6]. The method is based on a new metric named Estimated Duty Cycled wake-ups (EDC) that reflects the expected number of duty-cycled waken nodes that are required to successfully deliver a packet from source to destination.

In [7], Yanjun Sun et al. present a new asynchronous duty-cycled MAC protocol, called Receiver-Initiated MAC (RI-MAC), which uses receiver-initiated data transmission in order to efficiently and effectively operate over a wide range of traffic loads. RI-MAC attempts to minimize the time a sender and its intended receiver occupy the wireless medium to find a rendezvous time for exchanging data, while still decoupling the sender and receiver's duty cycle schedules.

In [8], an asynchronous duty cycle adjustment MAC protocol ADCA is proposed. ADCA is a sleep/wake protocol to reduce power consumption without lowering network throughput or lengthening transmission delay. It is asynchronous; it allows each node in the WSN to set its own sleep/wake schedule independently. The media access is thus staggered and collisions are reduced. According to the statuses of previous transmission, ADCA adjusts the duty cycle length for shortening transmission delay and increasing throughput.

2.2 Expected Network Lifetime

In [9], Lei Shu et al. focus on the efficient gathering of multimedia data in WSNs within an expected lifetime. An adaptive scheme to dynamically adjust the transmission Radius and data generation Rate Adjustment (RRA) is proposed based on a cross layer designed by considering the interaction among physical, network and transport layers.

Lei shu et al. also propose a situation where applications generally expect that WSNs can provide continuous streaming data during a relatively short expected network lifetime. Then they solve two basic problems: 1) gathering as much data as possible within an expected network lifetime, 2) minimizing transmission delay within an expected network lifetime [10].

2.3 The RS and CKN Sleep Schedule Algorithm

In RS sleep schedule networks, each sensor keeps an active-sleep schedule independent of another, thus the network is essentially a collection of independent active or sleep process. Hereby we assume the sleep ratio as 1-β ($0 < \beta < 1$).

CKN sleep schedule is adopted for duty-cycled WSNs. It allows a portion of sensor nodes going to sleep but still keeps all awoken sensor nodes k-connected to elongate the lifetime of a WSN, i.e. every node has k awake neighbors. In terms of that, the following conditions should be guaranteed.

- Each node in the WSN has at least $m{=}min(k;\, |Nu|)$ awake neighbors.
- All awake nodes are connected.

2.4 Our Novelty

As a conclusion, while above literatures either concern with expected network lifetime or duty-cycled sleep schedule, or neglect the amount of data collection. We propose a way to find most superior parameters to collect the most amount of data in a specific CKN based network. We make a comparison of energy consumption between CKN and RS sleep schedule, then we further show the results after simulation.

3 Our Approach

3.1 Assumptions and Notations

We consider a set of N wireless sensor nodes (hereafter refers to nodes) uniformly distributed in a square area A. Thus node density is ρ. Each node u has same transmission radius R. As long as an awake node u is in the transmission area of another awake node v, we consider they can communicate with each other, and a number of nodes s form a communication graph called G_s. N_u and $N_u{}'$ is the set of node u's 1-hop neighbor nodes, C_u and $C_u{}'$ is the subset of N_u and $N_u{}'$ under special condition in CKN algorithm. The expected network lifetime until the first node drained of its energy is defined as ELT. ELT is divided into many epochs, which also can be call round. In each round, nodes execute sleep schedule once. Thus the timespan of each round is defined as T, and we use R_d to denote the number of T. We assume all above parameters are the same in RS networks and CKN networks. Let DC be the total amount of data collection by all nodes. Parameters and the initial values are listed in Table 1.

3.2 RTS/CTS Model and First Order Radio Model

As mentioned in [11], under RTS/CTS interference, we get the probability that a node sends a packet P_S equals to the probability that a node receives a packet P_R is

$$P = P_S = P_R = \frac{2AC_1}{N\pi R^2} \tag{1}$$

and the probability that a node keeps idle P_I is

$$P_I = 1 - 2P \tag{2}$$

where C_1 subjects to (3) which is related to the specific network.

$$C_\varepsilon \leq (6\varepsilon + 1)^2 + 11 \tag{3}$$

Each node is equipped with single interface, and has the same initial energy available. Our energy model for nodes is based on the first order radio model [12] where the radio dissipates to power the transmitter or receiver circuitry, and for the transmit amplifier. E_{elec} is the energy required for transceiver circuity to process one bit of data, E_{amp} is the energy required per bit of data for transmitter amplifier, d is the communication radius of node u. Energy consumption to send a l-bit message over distance R is

$$E_S(l, R) = E_{elec}l + E_{amp}ld^2 \tag{4}$$

While transmitter amplifier is not needed by node u to receive data and the energy consumed by node u to receive a l-bit data packet is

$$E_R = E_{elec} * l \tag{5}$$

while E_I, the energy consumed by nodes with the radio in the idle model, is approximately the same with the radio in the receiving mode, i.e.,

$$E_I = E_R \tag{6}$$

Table 1. Parameter definition

Parameter	Definition
$\lvert . \rvert$	The number of network elements in a set
N	Number of sensor nodes in the network
U	Set of sensor nodes
R	Node transmission radius
A	Network area
ρ	Node density
M	Number of packets
T	The unit epoch of time
R_u	Set of node u's neighbors' ranks
k	The determining value in CKN algorithm
$1-\beta$	Sleep ratio in RS schedule
$rank_u$	Random rank of node u
E_S	Consumed energy to transmit a packet represented by l bits over distance d
E_R	Consumed energy to receive a packet represented by l bits over distance d
E_I	Consumed energy to keep idle
P_{asleep}	Probability of sleep state with CKN
P_{awake}	Probability of awake state with CKN
P_{idle}	Probability of idle state with CKN
$N_u/N_u{}'$	The set of node u's 1-hop neighbors and 2-hop neighbors
$C_u/C_u{}'$	The sub set of $N_u/N_u{}'$ whose $rank \leq rank_u$
DC	Data collection of the whole network

3.3 Some Probabilities in CKN Schedule

As mentioned above, CKN algorithm can be described as following two phases.

- Graph $G_{C_u+C_u{}'}$ is connected.
- Graph G_{N_u} is k-connected by nodes in C_u.

The probabilities of two phases are P_{rob1} and P_{rob2}, respectively. With ρ is node density

$$\rho = \frac{N}{A} \tag{7}$$

Moreover, the probability that the communication graph G is k-connected can be calculated as the probability that there exists at least k different paths connecting any two different vertices in the graph which is

$$P_{(G_{k-connected})} = (1 - \sum_{n=0}^{k-1} \frac{(\rho\pi R^2)^n}{n!} e^{-\rho\pi R^2})^N \tag{8}$$

here

$$\rho' = \frac{|U'|}{A} \tag{9}$$

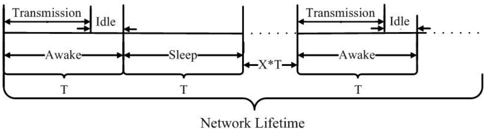


Fig. 1. Node's sleep schedule in RS networks

then we can get that the probability that graph $G_{C_u+C_u{}'}$ is connected is

$$P_{rob1} = (1 - e^{\rho' \pi R^2})^{(|C_u|+|C_u{}'|)} \tag{10}$$

and the probability that graph G_{N_u} is k-connected by nodes in C_u is

$$P_{rob2} = (1 - \sum_{n=0}^{k-1} \frac{(\rho' \pi R^2)^n}{n!} e^{-\rho' \pi R^2})^{|C_u|} \tag{11}$$

Thus the sleep probability and awake probability of node u is

$$P_{awake} = 1 - P_{rob1} * P_{rob2} \tag{12}$$

$$P_{asleep} = P_{rob1} * P_{rob2} \tag{13}$$

3.4 Energy Consumption of RS Networks

As aforementioned, in RS networks, nodes sleep ratio is 1-β, β is a random value between 0 and 1. It is well known that nodes energy is mainly consumed in their active epoch, while the energy consumption in sleep epoch can be neglected.

Fig. 1 shows a nodes' sleep schedule in a single epoch in RS networks. In an awake state, nodes turn on their transmit unit, keep transmitting or keep idle, both consumed a lot of energy. But with a certain probability β, nodes transfer into sleep state and save energy. Thus the energy consumption of RS networks is equal to

$$E_T = T\beta M[P_S E_S - P_R E_R + E_R]{=}T\beta M E_1 \tag{14}$$

3.5 Energy Consumption of CKN Networks

Fig. 2 depicts a node's sleep schedule adopting CKN. At the beginning of each single epoch, it costs node T_1 to execute CKN algorithm automatically, we assume T_1 is bound to ω, which is related to the specific network.

$$T_1{=}\omega T (0 < \omega < 1) \tag{15}$$

Then node's state in the rest time of epoch depends on the executive results. Thus time and energy consumption can be calculated if other parameters are fixed.

Therefore, the energy consumption of CKN network can be caculated by

$$\begin{aligned} E_{ckn-T} = & P_{awake}\{E_{ckn} + T_1[P_S E_S + P_R E_R + \\ & (1-2P)E_I]M\} + P_{asleep} E_{ckn} \end{aligned} \tag{16}$$

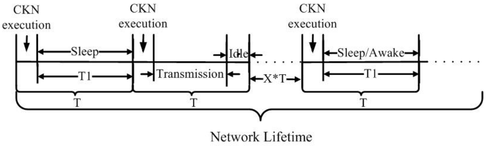


Fig. 2. Node's sleep schedule in CKN networks

3.6 Key Parameters

For the sake of clarity, we denote DC as

$$DC = R_d * N_{act} = \frac{ELT}{T} * N_{act} \tag{17}$$

In (17), N_{act} is the number of nodes which worked or is awaking. With this condition satisfied, DC can be determined by ELT, T and N_{act}. We need to guarantee that CKN networks is more energy efficient, i.e. $E_{ckn-T} < E_T$. Thus (14) and (16) allow us to have a lower bound of T to satisfy this condition

$$T > \frac{E_{ckn}}{ME_1(\beta - \omega P_{awake})} \tag{18}$$

As aforementioned, k is a specific value in CKN algorithm, N is the number of nodes which is changeable with specific WSNs applications, R is transmission radius that varying according to node's power level. Based on those previously analysis, we define k, N, and R is the three regulable parameters as well as expected network lifetime ELT.

The pseudo code of our approach is showed as follows.

```
Require:
  $E_T$ ⇐the energy consumption of WSNs under RS sleep schedule
$E_{ckn-T}$ ⇐the energy consumption of WSNs under CKN sleep schedule
if $E_T$ >$E_{ckn-T}$ then
    Find the determine $T$
else
    return
end if
Determine the datacollection with different values
while datacollection reaches maximum do
    return most optimal parameter values.
```

4 Simulation and Results

4.1 Simulation Settings

All the simulations are implemented with MATLAB. Table 1 shows the simulation parameters.

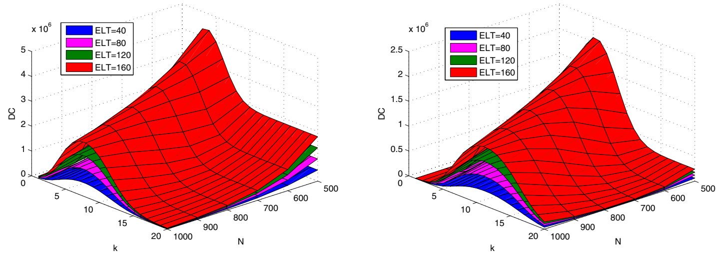
Table 2. Simulation parameters

Parameters	values
Network size(m^2)	600*800
N	500-1000
k	1-20
$R(m)$	50,60,70
$LT(h)$	40,80,120,160
C1	60
$E_{elec}(J)$	50e-9
$E_{amp}(J)$	0.1e-9
$l(bit)$	1024
M	100
ω	0.8
β	0.5

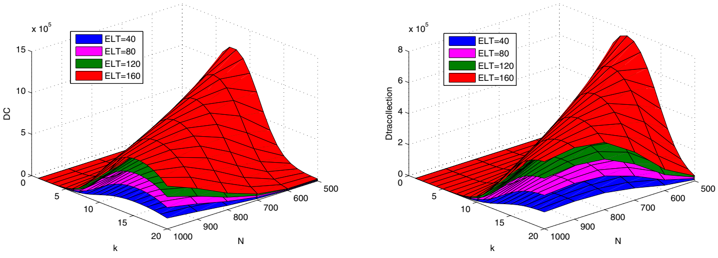
4.2 Simulation Results

The variation trend of DC with different k, N and ELT as well as R is shown from Fig. 3 to Fig. 5. The x-axis denotes the total node number N in the sensing area, the y-axis represents k, and z-axis stands for DC. The four different colors stand for different ELT as shown in each figure. Since A is fixed, we can regulate node density ρ by changing the number of nodes N.

Fig. 3 shows the variation of DC from different angles when R is $50m$, $60m$, $70m$ and $80m$. Four curved surfaces of different colors refer to $40h$, $80h$, $120h$ and $160h$ expected network lifetime respectively. The variation tendency of DC is like a shape of saddle. Four curved surfaces in each figure gets their maximum values of DC at the same k when N is fixed. For instance, in Fig. 3(a) when N is fixed to 500, four curves achieve their maximum values of DC when k is equal to 4, while N is fixed 800, the maximum value of DC can be found at k equals 6. Fig. 3 (b),(c) and (d) reflect that the longer network lifetime is, the more DC achieved, but not proportional. This can be explained as follows. When k reaches a certain point, under CKN algorithm, most nodes are awake to insure that there is at least k awake neighbors during network lifetime. DC and T can be calculated by (17) and (18) respectively. Equation (18) reflects the fact that T increases rapidly as P_{asleep} increases consistently, and P_{asleep} is closely related to k. As a result, DC decreases gradually. The more awake nodes, the more energy consumed. If the energy consumption in CKN network becomes larger than a certain threshold value and even larger than the energy consumption of RS algorithm, CKN algorithm will lose its superiority. This simulation results show that we can realize the maximum data collection in CKN networks when preseted N and k under expected network lifetime. When ω and N are fixed to 0.5 and 600 respectively which means node density is fixed, while other parameters are identical to Table I, the variation of DC with different transmission radiuses (from $10m$ to $150m$) is shown in Fig. 4. It is clear that R, k and ELT have a significant influence on the data collection. In Fig. 4(a) and Fig. 4(b), the



(a) R=50 (b) R=60



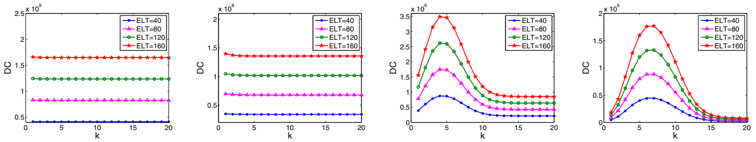
(c) R=70 (d) R=80

Fig. 3. The variations of DC when R is $50m$, $60m$, $70m$ and $80m$, respectively

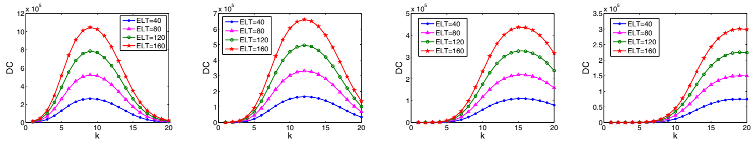
value of DC is much larger than others. It is mainly due to the fact that the shorter transmission radius is, the less energy consumed during the transmission period. While in Fig. 4(c) to Fig. 4(h), the relationship between k and DC is an approximate quadratic curve. That is to say, when R varies from $50m$ to $100m$, there always exists an optimal value of k to achieve maximum DC. When R is equal to $130m$ or $150m$, it seems that the variation tendency of curves is different from previous as shown in Fig. 4(i) and (j). However, Fig. 4(k) and (l) reflect that an approximate quadratic equation also can be found to express parts of the curve when k is large enough. In real applications, k should have appropriate boundaries, neither too large nor too small. In this paper, we do not discuss the boundaries of k, just try to find the relationships among these parameters. These results give a straight solution of finding the most appropriate k to achieve maximum data collection under CKN algorithm.

5 Conclusions

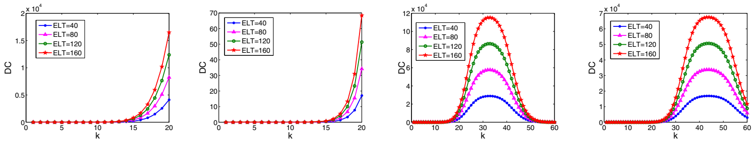
This paper proposes a CKN based energy saving approach to optimize network parameters. In the proposed approach, we assume nodes in WSNs is working according to Connected k-Neighborhood sleep schedule. We provide a theoretical analysis on the energy consumption of networks adopting CKN sleep schedule and RS schedule, then find a bound value to insure the superiority of CKN



(a) R=10m (b) R=20m (c) R=50m (d) R=60m



(e) R=70m (f) R=80m (g) R=90m (h) R=100m



(i) R=130m (j) R=150m (k) R=130m (l) R=150m

Fig. 4. The variations of DC under different R and ELT(In order to make a comparison, k varies from 1 to 60 in (k) and (l)).

algorithm. Simulation results depict the relationship between data collection and other three different network parameters. Performance analysis can help to select the most appropriate network parameters under expected network lifetime.

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