Proceedings of 2013 IEEE
International Conference on Mechatronics and Automation
August 4 - 7, Takamatsu, Japan

Optimized Energy-Latency Cooperative Transmission in Duty-Cycled Wireless Sensor Networks

Yu Wang
Department of Computer Science and Technology
Xi'an Jiaotong University
Xi'an, Shaanxi, China
chloe.wangyu@yahoo.cn

Shuxiang Guo
Department of Intelligent Mechanical Systems Eng'g
Kagawa University
Takamatsu, Japan
guo@eng.kagawa.-u.ac.jp

***Abstract*— Aiming to maximum the lifetime of battery-powered sensors, many research efforts concentrate on sleep schedule that provides duty cycles for nodes to cut down energy consumptions in idle listening. However, this energy-efficient approach introduces the data delivery latency issue in wireless sensor network(WSNs). In order to balance latency and energy in duty-cycled WSNs, we exploit the range extension feature of cooperative communication to tackle this issue. In the paper, we first present the way of applying cooperative communication so as to reduce latency. Then, based on the formulated energy model, we come up with the solution to minimize the end-to-end energy expenditure. Finally, according to above analysis, an energy-efficient and delay-tolerant cooperative transmission algorithm(EDTCT) is proposed. The experiments validate that our EDTCT algorithm outperforms the traditional routing way both in end-to-end sleep latency and energy savings.**

***Index Terms*— Cooperative Transmission, Energy-Efficient, Latency, Duty-cycle, WSNs**

I. Introduction

Recently, wireless sensor networks(WSNs) has a wide range of applications [1]. In WSNs, hundreds of sensor nodes are distributed in outdoor field and typically powered by batteries. When energy depleted, replacement of batteries is impractical due to large number of the sensors and unattended environment. Therefore, energy conservation is a critical concern in WSNs. In order to achieve energy savings, most of existing work puts the radio transceiver into sleep state periodically because transceiver is the most power-hungry module of node. This effective energy conservation behavior is called duty cycling where nodes switch their radios on and off periodically so as to use nodes' limited energy efficiently. Such work about duty-cycle schemes can refer to [2] [3].

Duty-cycle approach benefits a lot in energy conservation. However, it results in performance degradation in transmission delay, which caused by sleeping nodes on the transmission route. Specifically, when the next hop is sleeping sender has to transmit packet in store-wait-forward way, which means when packet destined to next sleeping hop arrives at sender, it has to buffer the packet and wait until the next hop wakes up. The time elapsed on sender is called sleep latency. If packet meets many sleeping node on route, sleep latency on each hop will accumulate and result in end-to-end(E2E) transmission delay.

To cope this issue, a number of research efforts have been paid to study on a tradeoff between energy savings and sleep latency reduction. We note that many asynchronous MAC protocols such as S-MAC [4], X-MAC [5] and RI-MAC [6] effective deal with energy problems compared with synchronous MAC. Nevertheless, these MAC protocols cause more sleep latency on each hop. Besides, several investigations like [7] [8] [9] [10], propose routing algorithms to find an energy efficient and low latency path based on determined sleep schedule. However, these schemes may be hard to find shortest paths.

Based on this motivation, our study aims to minimize the sleep latency combined with transmission energy optimization on the existed shortest path. In order to minimize delay, we consider to exploit range extension feature of cooperative communication(CT) by jumping over these sleep nodes. In this paper, we first develop the basic idea of how CT works on transmission route. Then joint with CT, we form the model of E2E transmission energy expenditure. Through analysis, we found that the solution to optimize transmission energy is to carefully make decision about relay selection. Finally, we propose an algorithm: EDTCT(Energy-efficient Delay Tolerant Cooperative Transmission). On one hand, EDTCT takes advantage of cooperative communication to deal with sleeping nodes, while on the other hand, it optimizes the relay selection process to achieve energy savings. The results show that our algorithm EDTCT outperforms the traditional way both in E2E delay and energy consumptions.

The paper is organized as follows: in Section II, we introduce the range extension feature of CT and develop the basic idea of how CT works on transmission route. We formulate the E2E energy consumption model and derive the analytical results in Section III. The EDTCT algorithm is described in Section IV and the performance evaluation of EDTCT is presented in Section V. Finally, we conclude the paper in Section VI.

978-1-4673-5558-2/13/$31.00

II. Basic Idea of Sleep Latency Reduction Scheme

In this section, we firstly briefly describe the principle of transmission range extension in cooperative communication. We then specify cooperative transmission used scenarios according to the states of sender's next two hops.

A. Transmission Rang Extension in CT

Cooperative communication, which takes advantage of the spatial diversity, requires assigned relays to help a sender forward encoded information to receiver. With the diversity gain, the signal can be transmitted at further distance in CT than that in direct transmission without diversity gain. According to [11], compared to direct transmission with transit power P and range d_{DT}, the CT transmission range d_{CT} with the same power P at each transmitter and diversity gain $G(N)$ will be

$$d_{CT} = d_{DT} \times 10^{(10\lg(N)+G(N))/10\lambda} \tag{1}$$

where N is the number of cooperators and λ is path-loss exponent. When the signal is modulated by BPSK at a bit error rate(BER) of 10^{-3} and only two node cooperate, the CT transmission range is 4 times longer than that of direct transmission($\lambda = 2$). This is called range extension in CT.

Therefore, instead of waiting next hop waking up in store-and-forward way, sender can cooperate with relay transmitting packet to the next two-hop node in active state through extending transmission range in CT. This collaborative process in each hop is illustrated in Fig.1. And only two nodes participating in cooperative transmission is enough.

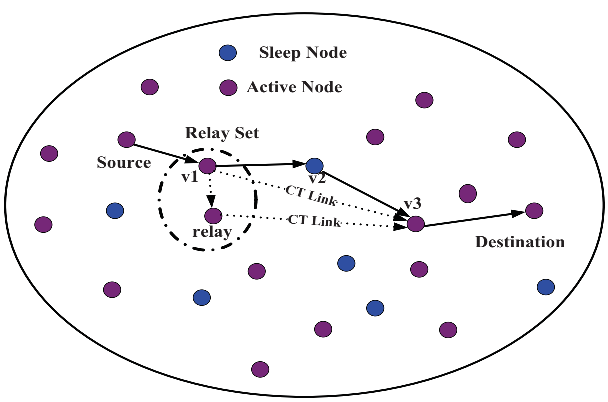

Fig. 1. An Example of Cooperative Transmission in Duty-Cycled WSNs

B. Cooperative Transmission Strategy

As stated above, we show the how range extension of cooperative communication works on transmitters. Next we discuss when transmitter makes decision about forwarding packet in cooperative way. Suppose v_1 need report to sink and there exists a shortest path$\{v_1, \ldots, v_i, v_{i+1}, v_{i+2}, \ldots, sink\}$. When packet reaching v_i and sender v_i will encounter four scenarios based on the states of next two hops. In the first scenario, sender v_i finds next hop in active state and v_i forwards packet to v_{i+1} directly. In the second scenario, the next hop is sleeping, whereas downstream two-hop distance node v_{i+2} is in active state. This situation incurs sender v_i with relay transmits packet cooperatively to active node v_{i+2} by extending range. Instead of waiting for next hop waking up, cooperative communication reduce the sleeping latency by jumping over the sleeping node v_{i+1}. However, if node v_{i+2} is sleeping too but fortunately it wakes up earlier than v_{i+1}, sender can still take cooperative transmission approach forwarding packet to v_{i+1}. This is the third scenario and CT reduces sleep latency in some extent. In the last scenario where the next two hops are both in sleeping states and v_{i+2} wakes up later than v_{i+1}, sender has no choice but take store-and-wait way forwarding packet to v_{i+1} directly.

The above four scenarios contains all conditions that sender may encounter when taking cooperative transmission and it is clear that because of extending range sleep latency has been reduced in the second and third scenarios.

III. Optimization of Transmission Energy Consumption

According to the two forwarding ways, in this section, we formulate and analyze E2E transmission energy consumption model and come up with solution to optimize energy.

A. Energy Model Formulation

Suppose v_1 need report to sink and the shortest path$R_h = \{v_1, \ldots, v_i, v_{i+1}, v_{i+2}, \ldots, sink\}$ already exists. Based on above four scenarios, transmitter sends packet either in direct way or in cooperative way. Thus, the optimization issue to minimize the E2E transmission power on R_h can be formulated as

$$\begin{aligned} &E_{Rh} = \min\Big(\sum_{i \in DTS} P_i^{DT} + \sum_{j \in CTS} P_j^{CT}\Big) \\ &s.t. \begin{cases} |DTS| + 2|CTS| + 1 = |R_h| \\ P_i^{DT} \leq P_{max} \end{cases} \end{aligned} \tag{2}$$

where P_i^{DT} and P_j^{CT} stand for direct transmission power and cooperative transmission power respectively. And the first term in 2 represents the sum of energy cost when node v_i adopts direct transmission and DTS is a set where node transmits packet in direct way. Similarly, the second term represents the total energy cost when node v_j employs cooperative transmission and CTS contains all the forwarders on route taking cooperative transmission.

The nodes in DTS and CTS are determined due to duty cycles already settled and the total direct transmission power is constant because the route is fixed. Consequently, the optimization problem can be simplified as minimizing the total cooperative transmission energy consumption. Next we formulate the power consumption models on direct transmission and cooperative transmission. Assume that the nodes equipped with a single omni-directional antenna and the channel is Rayleigh fading model with additive white Gaussian noise.

1) Energy Consumption in Direct Transmission: The receiver can decode the signal correctly if the received SNR(signal noise ratio) is larger than minimum threshold value SNR_{min}. Thus, the minimum the energy cost in direct transmission is described as

$$P_{sd}^{DT} = \frac{SNR_{min}P_{\eta}}{E[\alpha^2]} d_{sd}^{\lambda} \tag{3}$$

where P_{η} and d_{sd} are noise power and distance between source and destination nodes respectively. And α is independent complex Gaussian random variable with zero-mean and unit variance.

2) Energy Consumption in Cooperative Transmission: In CT, sender first shares packet with relay and then they two forward packet to destination cooperatively. Hence, the energy cost consist of two parts: one for broadcast packet to relay P_s^B and the other for cooperative communication P_s^C. Because one relay collaborating with sender is enough for range extension. The first part energy is

$$P_s^B = P_{sr}^{DT}, r \in NS(s) \tag{4}$$

where $NS(s)$ is the neighbor set of sender s.

For the second part, sender s and relay r simultaneously transmit packet to destination and the signals are added up at receiver. The energy cost in second part is expressed as

$$P_s^C = \frac{SNR_{min}P_{\eta}}{E[\alpha^2](d_{sd}^{-\lambda} + d_{rd}^{-\lambda})} \tag{5}$$

Therefore, the total energy consumption in cooperative transmission is obtained as

$$P_s^{CT} = \frac{SNR_{min}P_{\eta}}{E[\alpha^2]} d_{sr}^{\lambda} + \frac{SNR_{min}P_{\eta}}{E[\alpha^2](d_{sd}^{-\lambda} + d_{rd}^{-\lambda})}, r \in NS(s) \tag{6}$$

Equation (6) presents that energy cost is mainly determined by distances d_{sr} and d_{rd}, which implies that relay position has great an influence on energy cost. If relay is close to destination, the second part costs energy less while resulting in more consumption in the first part and vice verse. Therefore, by weighing the distance d_{sr} and d_{rd}, it is necessary to explore the relation between energy consumption and relay position.

B. Analysis

For further analyzing the relation between relay position and energy consumption in cooperative transmission, we set $\lambda = 2$ and let θ represent the angle between source-relay and source-destination, where $\theta \in [-\frac{\pi}{2}, \frac{\pi}{2}]$. To facilitate derivation, (6) can be approximated as the following formula based on Harmonic inequality:

$$\Gamma(d_{sr}, \theta) = \frac{SNR_{min}P_{\eta}}{E[\alpha^2]}(\frac{5}{4}d_{sr}^2 - \frac{1}{2}d_{sd}d_{sr}\cos\theta + \frac{1}{2}d_{sd}^2) \\ s.t. 0 < d_{sr} \le d_{max} \tag{7}$$

Through taking partial derivatives, we have

$$\begin{cases} \frac{\partial\Gamma(d_{sr},\theta)}{\partial\theta} = \frac{1}{2}d_{sd}d_{sr}\sin\theta, & \theta \in [0, \frac{\pi}{2}] \\ \frac{\partial\Gamma(d_{sr},\theta)}{\partial d_{sr}} = \frac{5}{2}d_{sr} - \frac{1}{2}d_{sd}\cos\theta, & 0 < d_{sr} \le d_{max} \end{cases} \tag{8}$$

Apparently $\frac{\partial\Gamma(d_{sr},\theta)}{\partial\theta)} \ge 0$, it implies that when the d_{sr} is given, cooperative transmission consumes less power as angle θ is small. Thus, when choosing relay from neighbor, the node approaches the line of source-destination is preferred to be the optimal relay. As $d_{sr} \ge \frac{1}{5}d_{sd}\cos\theta \Rightarrow \frac{\partial\Gamma(d_{sr},\theta)}{\partial d_{sr}} \ge 0$, it proves that the minimal d_{sr} exists and it's relevant to angle θ. When θ is given, energy consumption declines first until d_{sr} nearly approaches $d_{sr} \ge \frac{1}{5}d_{sd}\cos\theta$ and then it increases.

For evaluate the energy consumption, we derive the upper bound on energy consumption in cooperative transmission, which means no matter where relay is energy cost won't exceed the upper bound. Actually, it is the function of two variables with constraint problem by finding the maximum value. The upper bound is $\Gamma(d_{max}, \pm\frac{\pi}{2}) = \frac{SNR_{min}P_{\eta}}{E[\alpha^2]}(1.45d_{max}^2 + 0.5d_{sd}^2)$. As shown in Fig. 2 that the upper bound is always

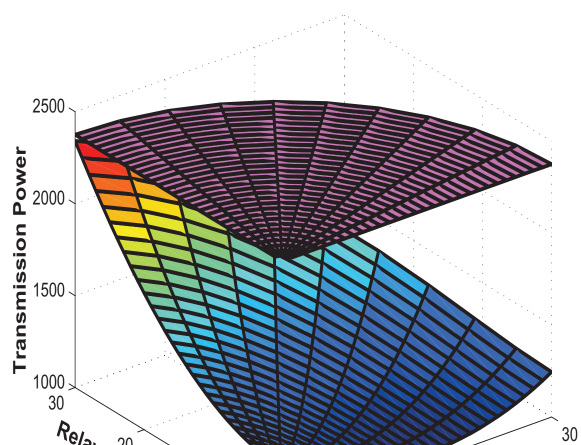

Fig. 2. An Example of Cooperative Transmission in Duty-Cycled WSNs

C. Optimization of Relay Selection

Based on above analysis, we get clues about how to select relay in sender's neighbors in order to reduce energy consumption in cooperative transmission. There are two aspects to consider in relay selection. One is the energy expenditure in CT which had been discussed above. The other is residual energies of neighbors. A good relay should consumes less energy and has more residual power. For taking these two aspects in account, we propose a metric ω_{sd}^r to qualify the best relay of sender s. The metric ω_{sd}^r is defined as

$$\omega_{sd}^r = \frac{d_{sr}^{\lambda} + \frac{1}{d_{sd}^{-\lambda} + d_{rd}^{-\lambda}}}{\frac{E_{residual}(r)}{E_{initial}(r)}} \tag{9}$$

The numerator of (9) represents the energy consumption of cooperative transmission with relay r and the denominator represents the relay residual energy ratio, where $E_{initial}(r)$ is the initial power of battery. The optimal relay r^* is selected from the neighbor set $NS(s)$ with minimal ω_{sd}^r as

$$r^* = min_{r \in NS(s)} \omega_{sd}^r \tag{10}$$

IV. Description of Energy-Efficient Delay-Tolerant Cooperative Transmission Algorithm

According the sleep latency reduction scheme and transmission energy consumption optimization stated above, we put forward an algorithm EDTCT(Energy-efficient Delay-tolerant Cooperative Transmission) to both balance sleep latency and energy expenditure in transmission. The EDTCT algorithm comprise two procedures: transmission modes determination procedure and relay selection procedure. The former one operated on node tackles with the sleep latency issue according to different four scenarios while the latter one is responsible for picking up an energy-efficient relay in order to save energy in cooperative transmission.

A. Transmission Modes Determination Procedure

In the transmission modes determination procedure, we model the sensor operating in one of two stats: sleep and active. For any nodes, the state of each node is independent and expressed with variable S_n^i,defined as

$$S_n^i = \begin{cases} 0, & \text{node in sleep state at the n-th time slots;} \\ 1, & \text{node in active state at the n-th time slots;} \end{cases} \tag{11}$$

WT_{i+1}^i denotes sleep latency that node v_i waits until next hop v_{i+1} wakes up. In this algorithm, we use Pseudo-random Number Generation(PRNG) algorithms [7] to predict the states of neighbors. The details of sender making decision about transmission modes are presented in Algorithm 1.

B. Relay Selection Procedure

Considering that WSN is of dense density, it takes time to search for the minimal ω in neighbors. Based on the analytical result that relay close to the line of source and destination is more likely to be the optimal forwarder, we propose to decompose the neighbor zone into several pieces of sectors with angle $\triangle\theta$ and these named PCA(Priority Candidate Area) are assigned with priority. Neighbors with small θ assemble in high priority sector resulting in low energy expenditure. Assuming that nodes are uniform distributed in the area with density ρ, the neighbor zone can be divided into $n_{PCA} = \lceil \frac{\pi}{2 \times \triangle\theta_{min}} \rceil$ pieces and $\theta_{min} = \frac{2m}{\rho \times d_{max}^2}$, where each PCA at least has m nodes. We appoint the PCA closest to line of source and destination with highest priority denoted as 1-thPCA and so forth. Consequently, PCA instructs sender choosing relay instead of random picking up in neighbors. The details of relay selection process is described in Algorithm 2.

Algorithm 1 Transmission Mode Determination Procedure at Node v_i

1: Check the sleep schedule of next hop v_{i+1} when v_i receiving message;
2: **if** $S_n^{i+1} = 1$ **then**
3: go to Step 18;{node v_i do direct transmission.}
4: **else**
5: check the sleep schedule of node v_{i+2};
6: **if** $S_n^{i+2} = 1$ **then**
7: go to Step 17;
8: **else**
9: Compare the waiting-time of v_{i+1} and v_{i+2};
10: **if** $WT_{i+1}^i \geq WT_{i+2}^i$ **then**
11: wait for WT_{i+2}^i slots and go to Step 17;
12: **else**
13: wait for WT_{i+1}^i slots and go to Step 18;
14: **end if**
15: **end if**
16: **end if**
17: Cooperative Transmission(CT): node v_i prepares to execute Relay Selection Procedure and collaborates with optimal relay forwarding packet to v_{i+2} cooperatively.
18: Direct Transmission (DT): node v_i transmits packet to v_{i+1} directly and exits the procedure;

Algorithm 2 Relay Selection Procedure at Node v_i

Require: node's energy and location information, ρ, m;
Ensure: ω_{min} and $Relay$;
1: Calculate n_{PCA} and $\triangle(\theta)$;decompose the neighbor area into priority candidate area.
2: $\omega_{min} \leftarrow \emptyset$,$Relay \leftarrow \emptyset$,;
3: **for** $i \leftarrow 1$ to n_{PCA} **do**
4: $S_{i-thPCA} \leftarrow \{j | (j \in i-thPCA) \cap S_j = 1\}$;
5: Calculate each $\omega^j, j \in S_{i-thPCA}$ and find neighbor r with minimal ω^r;
6: $\omega_{min} \leftarrow \omega^r$,$Relay \leftarrow r$;
7: **if** $Relay \neq \emptyset$ **then**
8: Break;
9: **end if**
10: **end for**

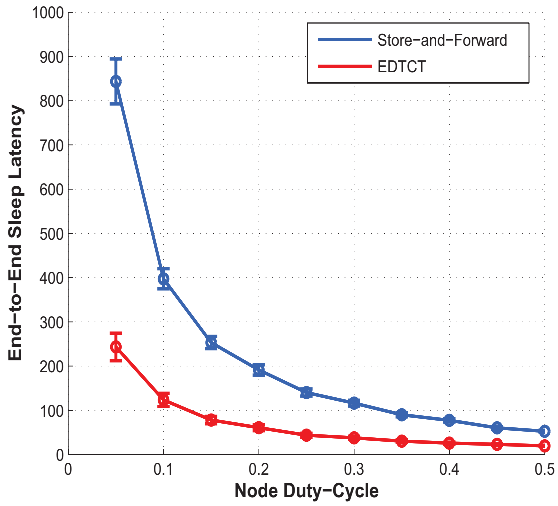

Fig. 3. The End-to-End sleep Latency vs. Duty Cycle, where hops is 10 and the number of neighbors is 4.

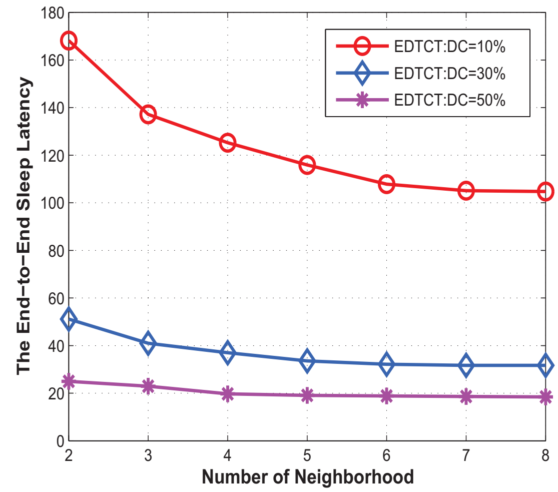

Fig. 4. The End-to-End sleep Latency vs. The Number of Neighbors, when duty cycle is set to 10%,30% and 50% respectively.

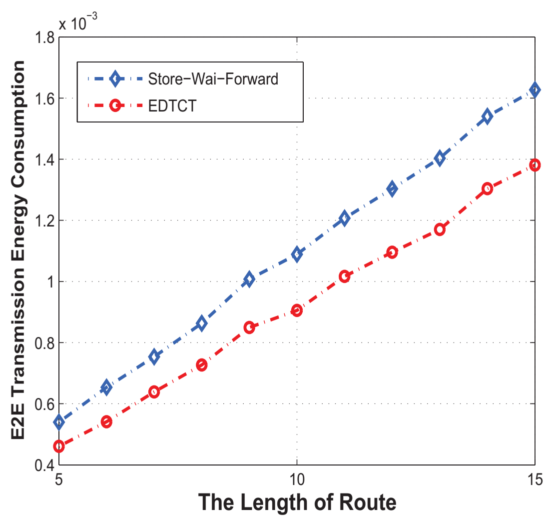

Fig. 5. End-to-End Transmission Energy Consumption vs. The Length of Hops, where duty cycle is 18% and the number of neighbors is 10.

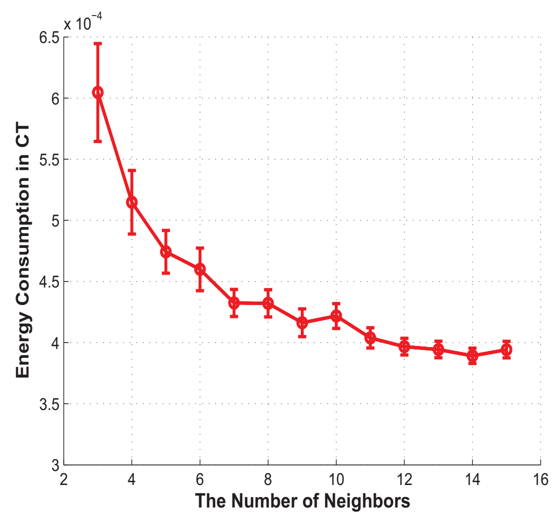

Fig. 6. End-to-End Transmission Energy Consumption vs. The Number of Neighbors.

V. Performance Evaluation

In this section, we evaluate the performances of sleep latency reduction and energy consumption savings in EDTCT and traditional way: store-wait-forward respectively. In our simulation, we assume the shortest route between source and destination is built and packets transmit on this route in two ways. The duty cycle of each node is independent and the durations of sleep and active state are uniform distributed random values in the range of $[1, K]$ and $[1, S]$ respectively, where K and S are the maximum time between two consecutive states. The transmission radius is 30 meter. Under the same path loss exponent $\lambda = 2$, the addictive white Gaussian noise power is $P_\eta = -70mdb$ and the SNR threshold is 3. In cooperative communication, signals are modulated by BPSK at BER of 10^{-3}. The simulation are implemented on Matlab 7.0 and each experiment is performed 200 trials random instance.

A. The E2E Sleep Latency vs. Node Duty Cycle

Fig.3 displays the correlation between the average E2E sleep latency and duty cycle when sender taking EDTCT and store-wait-forward ways. Obviously E2E sleep latency in EDTCT is smaller than that of store-wait-forward way. It demonstrates that the range extension of cooperative communication realizes the reduction of sleep latency by jump over the sleeping node. In particular, the reduction extent is larger when duty cycle is small and this result proves that EDTCT adapts in low-duty-cycled WSNs which conserve more energy. As duty cycle reaches 50% the sleep latency is very close both in two ways. The main reason is that the probability of next hop in active is high as duty cycle increases and sender is more likely to transmit packet directly to next hop.

B. The E2E Sleep Latency vs. The Number of Neighbors

Fig.4 shows how the number of forwarder's neighbors affects cooperative transmission in EDTCT when duty cycle is 10%, 30%, 50% respectively. As we can see, the E2E sleep latency firstly decreases as the number of neighbors increases and then it keeps constant. The reason is that increasing the number of neighbors gives more chances to sender doing cooperative transmission and reduces sleep latency. When the network is sparse, it's possible that no active neighbor exists to cooperate forwarder transmitting packet. Instead, sender has no choice but to take store-wait-forward way resulting in much sleep latency. In addition, compared to high duty cycle(duty cycle=30% and 50%), the network density has more influence on EDTCT when nodes duty cycle is low because the number of neighbors in active is little when duty cycle is low leading to cooperative transmission failure. Therefore, Fig.4 suggests that when EDTCT algorithm works in dense WSNs, it will be more efficiently.

C. The E2E Transmission Energy Consumption vs. The Length of Route

Fig.5 exhibits the comparison of the E2E transmission energy consumptions in EDTCT and store-wait-forward ways. As we can see, EDTCT is more energy efficient than store-wait-forward way. Besides, the energy benefit becomes more as the route grows longer. When the route is 5 hops, EDTCT reduces energy of 14.7% and when the route is 10 hops, EDTCT costs less 17% energy of store-wait-forward way. In summary, by applying cooperative communication in forwarding, our scheme achieves the goal of energy cost reduction.

D. Energy Consumption in CT vs. The Number of Neighbors

Fig.6 depicts the relation between the network density and energy consumption in cooperative transmission. As we can see, the energy cost decreases first and then it is prone to constant as the number of neighbors increase from 3 to 15. The main reason is that more number of neighbors give forwarder more choices of picking optimal relay according to selection metric ω. This result is accordance with the E2E delay shown in Fig.4 that EDTCT algorithm performs well in dense WSNs.

VI. Conclusion

In this paper, we aim to minimize sleep latency combined with transmission energy optimization. To address delay issue, we take advantage of range extension feature of cooperative communication so as to avoid waiting sleep node. Particular, we specify the scenarios that cooperative communication can be implemented on sender. Then joint with cooperative transmission, we formulate the energy consumption model and provide the solution to energy optimization. Finally, an energy-efficient and delay-tolerant cooperative transmission algorithm(EDTCT) is proposed. The simulations validate that EDTCT outperforms the store-wait-forward way no matter in E2E sleep latency and E2E energy consumption. In particular, our scheme is adaptive to dense network and it works efficiently in low-duty-cycled WSNs.

References

[1] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Computer networks*, vol. 52, no. 12, pp. 2292–2330, 2008.

[2] D. Messaoud, D. Djamel, and B. Nadjib, "Survey on latency issues of asynchronous mac protocols in delay-sensitive wireless sensor networks," 2012.

[3] G. Anastasi, M. Conti, M. Di Francesco, and A. Passarella, "Energy conservation in wireless sensor networks: A survey," *Ad Hoc Networks*, vol. 7, no. 3, pp. 537–568, 2009.

[4] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *Proceedings of the 2nd international conference on Embedded networked sensor systems*, SenSys '04, (New York, NY, USA), pp. 95–107, ACM, 2004.

[5] M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks," in *Proceedings of the 4th international conference on Embedded networked sensor systems*, SenSys '06, (New York, NY, USA), pp. 307–320, ACM, 2006.

[6] Y. Sun, O. Gurewitz, and D. B. Johnson, "Ri-mac: a receiver-initiated asynchronous duty cycle mac protocol for dynamic traffic loads in wireless sensor networks," in *Proceedings of the 6th ACM conference on Embedded network sensor systems*, SenSys '08, (New York, NY, USA), pp. 1–14, ACM, 2008.

[7] R. Beraldi, R. Baldoni, and R. Prakash, "A biased random walk routing protocol for wireless sensor networks: The lukewarm potato protocol," *Mobile Computing, IEEE Transactions on*, vol. 9, no. 11, pp. 1649–1661, 2010.

[8] Y. Gu and T. He, "Dynamic switching-based data forwarding for low-duty-cycle wireless sensor networks," *Mobile Computing, IEEE Transactions on*, vol. 10, no. 12, pp. 1741–1754, 2011.

[9] M. Zorzi and R. Rao, "Geographic random forwarding (geraf) for ad hoc and sensor networks: multihop performance," *Mobile Computing, IEEE Transactions on*, vol. 2, no. 4, pp. 337–348, 2003.

[10] V. Paruchuri, S. Basavaraju, A. Durresi, R. Kannan, and S. Iyengar, "Random asynchronous wakeup protocol for sensor networks," in *Broadband Networks, 2004. BroadNets 2004. Proceedings. First International Conference on*, pp. 710–717, 2004.

[11] G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, P. V. Krishnamurthy, and O. Ercetin, "A cross-layer framework for exploiting virtual miso links in mobile ad hoc networks," *Mobile Computing, IEEE Transactions on*, vol. 6, no. 6, pp. 579–594, 2007.