

An Adaptive Transmission Scheme for Wireless Sensor Networks

Weiwei Fang¹, Quan Zhou², Zishuo Wang¹ and Qiang Liu¹

¹*School of Computer and Information Technology, Beijing Jiaotong University,
Beijing, 100044, P.R. China*

²*School of Economics and Management, Beijing Jiaotong University,
Beijing, 100044, P.R. China*

{wwfang, 11120716, 09281154, liuq}@bjtu.edu.cn

Abstract

Cooperative communication is a promising technique for combating the effects of channel fading by exploiting diversity gain achieved via node cooperation. However, how to apply it into sensor networks in a feasible and efficient manner still remains as a problem. To address the issue, this paper proposes a new adaptive transmission scheme, which adaptively adjusts transmission mode between direct communication and cooperative communication for node pairs to achieve energy efficiency in wireless sensor networks. The scheme is implemented by a simple yet effective cross-layer design between the network and MAC layers. Extensive simulation results are presented to illuminate the distinguished performance of the proposed scheme.

Keywords: *Wireless Sensor Network, Cooperative Communication, Energy Efficiency*

1. Introduction

In recent year, the technological advances in micro-electro-mechanical systems and wireless communications have motivated the development of wireless sensor networks (WSNs). A WSN system is typically composed of nodes powered by batteries for which replacement or recharging is very difficult or even impossible. Therefore, improving the energy efficiency for data transmission becomes an important design issues for WSNs. However, the channel fading and packet error have a significant impact on transmission reliability and energy efficiency of WSNs [1]. To prolong the network lifetime, it is imperative to design for WSNs new approaches that can achieve high robustness while minimizing energy consumption.

It has been recently shown that multiple nodes can collaborate to improve network reliability and reduce energy consumption by utilizing the broadcast nature of wireless medium and the spatial distribution of sensor nodes. Such a strategy is generally termed as cooperative communication [2]. There are two types of cooperation: multiple-relay based and single-relay based. The former is achieved by distributed space-time coding [3] or distributed beamforming [4], and thus the implementation complexity and the cooperation overhead are relatively higher than the latter [5]. Therefore, the single-relay cooperative strategy is practically much more appealing for resource-constrained WSNs.

In the direct transmission (*i.e.*, non-cooperative) scheme, the packet transmission only involves the source and destination nodes, while the other neighboring nodes can be put into sleep state for energy saving. By choosing one node out of a set of potential candidates to aid the communication process, the single-relay cooperative transmission scheme can significantly reduce the transmission energy required for a successful data

transmission. However, at least a relay node has to be kept active, which might increase energy consumption. It is still unknown that which transmission mode is more energy efficient for a successful packet transmission. However, to design an energy-efficient transmission scheme for energy-constrained WSNs is still a challenging problem. By theoretical analyzing, this paper proposes an adaptive transmission scheme which can adaptively adjust the transmission mode based on the source-destination distance for achieving energy efficiency. The scheme is implemented by cross-layer design between the network layer and the MAC layer. The CSMA MAC that is widely used in WSNs is revised to make it support adaptive transmission. The performance of this new scheme is evaluated through extensive simulations.

The remainder of this paper is organized as follows. Section 2 presents related works. We describe the design details of our scheme in Section 3. Section 4 illustrates the simulation and discusses the simulation results. Section 5 concludes the paper.

2. Related Works

There is already some existing works focusing on using cooperative communication for performance improvement in wireless networks. We refer to ExOR [6], MDR [7] and CoopMAC [8] as the typical earlier works on this topic. However, these works are designed for traditional wireless networks (*e.g.*, WLAN and MANET), and can't be directly used due to the unique challenges of WSNs [1].

Recent studies on cooperative communication have considered the specific properties of WSNs. Some of them focus on multiple-relay cooperative transmission, in which cooperation is performed between the clusters of sensor nodes [1, 9] in a MIMO-like communication manner. However, the complexity and overhead is very high for WSNs. On the other hand, some works are based on single-relay cooperation. SPaC [10] allows sensor nodes to buffer overheard corrupted packets and recover the original packet by combining multiple corrupt copies. SPaC has high requirements on storage space and computation overhead of sensor nodes. In [11], the receiver node combines the received signal for the source and the relay for joint decoding, and is not efficient for packet recovery since cooperation is only needed when the receiver fails to decode the original signal. A similar idea on cooperative MAC (COMAC) has been proposed in [12], but requires nodes equipped with 802.11g radios. The strategy for selecting the best relay for achieving fairness is studied in [13].

However, few attempts have been done on the energy efficiency issue of single-relay cooperation in WSNs. Existing works [5, 14, 15] mainly concentrate on theoretical work and only provide analytical results without any practical protocol design. In [16], the authors address the problem of joint design of routing, MAC, and physical layer protocols with cooperative communication to minimize energy cost in packet error rate constrained WSNs. However, this work assumes the adoption of TDMA MAC protocol, which is still not mature and capable enough to be used in the WSNs.

3. An Adaptive Transmission Scheme for Wireless Sensor Networks

Consider the example wireless network depicted in Figure 1, in which a source node s wants to send a packet to the destination node d . In the traditional non-cooperative scheme, the data transmission just involves the node s and d . In the single-relay based cooperation scheme, the transmission is usually divided into two phases. In the first phase, s transmits a data packet to d , and the relay node r can overhear this data packet due to the wireless broadcast advantage. In the second phase, the operation is performed

based on the reception result at d . If d receives the data packet successfully, then it sends an ACK to s while r is just idle. If d fails to receive the data packet while r has obtained a packet copy successfully through overhearing, and link (r, d) is better than the link (s, d) , r can forwards the data packet to d . Otherwise, the current transmission ends with failure, and s will start a new transmission for this data packet to d .

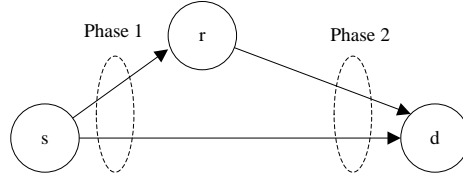


Figure 1. A Typical Data Transmission Scenario

Although the cooperation of r can help to save energy of s required for successful packet transmission, such cooperation involves two transmitting nodes (*i.e.*, s and r) and might increase energy consumption. Therefore, which one is more energy efficient and to what extent this one could save energy consumption for a successful packet transmission still remains unclear. For the energy-constrained WSN, it is important that the design of transmission scheme can minimize energy consumption for data gathering.

3.1. Analysis on Energy Efficiency of Data Transmission

Consider a flat Rayleigh fading channel, the average signal to noise ratio (SNR) γ at the receiver side is

$$\gamma_{ij} = \frac{Gp_t}{N_0 r_{ij}^\alpha} \quad (1)$$

where p_t denotes the transmit power that is constant for all nodes, N_0 denotes the variance of Additional White Gaussian Noise (AWGN), r_{ij} denotes the distance of node i and j , α denotes the path loss exponent, and G is a constant that is defined by the signal frequency, antenna gains, and other parameters [1].

Assume that M-QAM is adopted for modulation, the closed-form expression for the average symbol error rate (SER) of M-QAM over Rayleigh channels is given by [17] as

$$P_{ij}^{SER} = 2 \left(1 - \frac{1}{\sqrt{M}} \right) \left(1 - \sqrt{\frac{3\gamma_{ij}}{2(M-1) + 3\gamma_{ij}}} \right) + \left(1 - \frac{1}{\sqrt{M}} \right)^2 \left[\frac{4}{\pi} \sqrt{\frac{3\gamma_{ij}}{2(M-1) + 3\gamma_{ij}}} \arctan \left(\sqrt{\frac{2(M-1) + 3\gamma_{ij}}{3\gamma_{ij}}} \right) - 1 \right] \quad (2)$$

Then, the packet error rate (PER) of a link is

$$P_{ij}^{PER} = 1 - \left(1 - P_{ij}^{SER} \right)^{\frac{L}{\log_2 M}} \quad (3)$$

where L is the packet frame length [17].

We define the energy efficiency of the transmission as in [5]

$$\omega = \frac{L(1 - P_{ij}^{PER})}{E} \quad (4)$$

where E is the energy consumption for one time of transmission of a data packet. ω represents the number of bits that can be transmitted successfully with unit energy consumption. The larger ω is, the better the energy is utilized.

Now we can evaluate the energy efficiency of direct transmission and cooperative transmission, respectively.

(1) Direct Transmission

The PER of direct transmission equals to the PER of the source-destination link, and can be given as

$$P_{DT} = P_{sd}^{PER} = 1 - \left(1 - P_{sd}^{SER}\right)^{\frac{L}{\log_2 M}} \quad (5)$$

According to [15], the total consumed energy for transmitting one data packet can be given as

$$E_{DT} = \frac{\left(\frac{P_t}{\varepsilon} + p_{ct} + p_{cr}\right)L}{R} \quad (6)$$

where $\varepsilon \in (0, 1]$ denotes the power amplifier efficiency, R denotes the bit rate of sensor node, and p_{ct} and p_{cr} represents the power consumption of circuit blocks of transmitter and receiver, respectively.

Then the energy efficiency of direct transmission is

$$\omega_{DT} = \frac{L(1 - P_{DT})}{E_{DT}} \quad (7)$$

(2) Cooperative Transmission

The PER in the single-relay based cooperative transmission scheme can be given as

$$\begin{aligned} P_{CT} &= 1 - \left[\left(1 - P_{sd}^{PER}\right) + P_{sd}^{PER} \left(1 - P_{sr}^{PER}\right) \left(1 - P_{rd}^{PER}\right) \right] \\ &= P_{sd}^{PER} \left(P_{sr}^{PER} + P_{rd}^{PER} - P_{sr}^{PER} P_{rd}^{PER} \right) \end{aligned} \quad (8)$$

Different from direct transmission, in cooperative communication there totally exist two possible cases of data transmission: if the transmission from s to d succeeds or the transmission of both from s to d and from s to r fail, the cooperation of r is not needed; otherwise, there will be an additional relaying transmission from r . The probabilities for these cases are $\left(1 - P_{sd}^{PER} + P_{sd}^{PER} P_{sr}^{PER}\right)$ and $\left(P_{sd}^{PER} \left(1 - P_{sr}^{PER}\right)\right)$. Therefore, the total consumed energy for transmitting one packet is discrete random variable, and can be statistically calculated as follows

$$E_{CT} = \frac{\left[\left(1 - P_{sd}^{PER} + P_{sd}^{PER} P_{sr}^{PER}\right) \left(\frac{P_t}{\varepsilon} + p_{ct} + 2p_{cr}\right) + \left(P_{sd}^{PER} - P_{sd}^{PER} P_{sr}^{PER}\right) \left(\frac{2P_t}{\varepsilon} + 2p_{ct} + 3p_{cr}\right) \right] L}{R} \quad (9)$$

Then the energy efficiency of direct transmission is

$$\omega_{CT} = \frac{L(1 - P_{CT})}{E_{CT}} \quad (10)$$

For clear comparison, we use the gain of energy efficiency [5] calculated as follows

$$g = \frac{\omega_{CT}}{\omega_{DT}} \quad (11)$$

According to the specifications of Mica2 motes [5], the following parameters are given for the comparison: $G = 1$, $\alpha = 4$, $N_0 = 10^{-13}$, $M = 16$, $\varepsilon = 0.75$, $p_t = 660$ mW [18], $P_{ct} = 97.8$ and $P_{cr} = 112.8$ mW [19]. Without lose of generality, we assume that the nodes s , d and r lie along a straight line, and the distance between r and d is $r_{rd} = \mu \times r_{sd}$ ($0 < \mu < 1$). The results of energy efficiency gain under different r_{sd} , L and μ are shown in Figure 2.

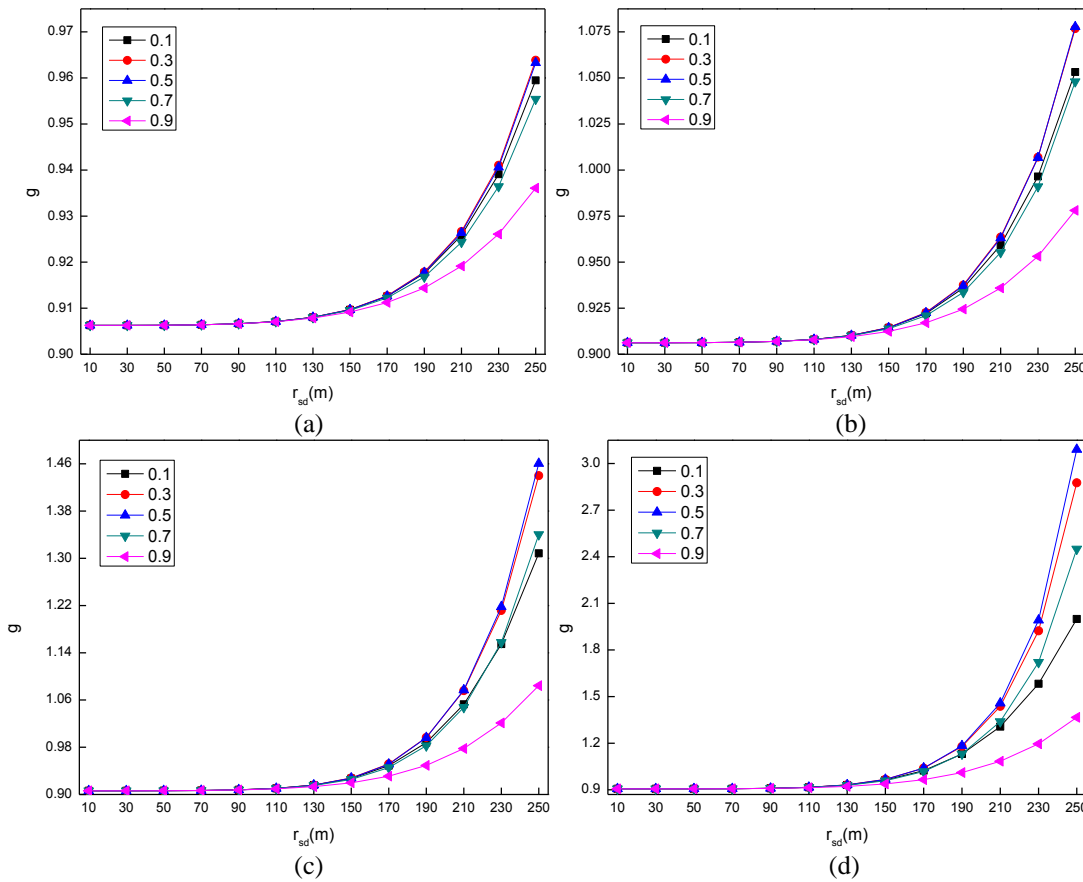


Figure 2. Energy Efficiency Gain under Different r_{sd} , L and μ Settings
 (a) $L = 32$ bytes; (b) $L = 64$ bytes; (c) $L = 128$ bytes; (d) $L = 256$ bytes

We have two main observations concerning the results in Figure 2. First, cooperative transmission is not always more energy efficient than direct transmission. It can be

noticed from Figure 2 that direct transmission is relatively more energy efficient when the packet length L is relatively small (*e.g.*, $L = 32$ bytes) or the distance r_{sd} is relatively small (*e.g.*, $r_{sd} < 150$ m). Second, the energy efficiency gain g is relatively highest when μ is around (*i.e.*, equal to or slightly less than) 0.5 in all the four cases. These findings provide useful guidelines for transmission mode selection and relay node selection in transmission protocol design.

3.2. Design Details of the Adaptive Transmission Scheme

According to the analysis in Section 3.1, it is necessary to design a new transmission scheme that can adaptively choose the transmission mode (*i.e.*, direct or cooperative) based on the relevant system parameters for achieving energy efficient data gathering. In current implementations, cooperation behaviors are not supported, *i.e.*, the overheard packet will be dropped silently by the relay candidates. This limitation motivates us to design the transmission scheme based on the current implementation and maintaining its original support to direct transmission.

Our scheme is based on a cross-layer design with MAC layer as the anchor, operated under the CSMA MAC [20]. To find a proper relay node for a source-destination pair, each sensor node is required to estimate its distance to each of neighboring nodes based on localization algorithms [21]. After that, the relay node can be determined through the method introduced in Section 3.1. The relay selection could be easily integrated into the process of topology management or routing management. In this manner, any node-pair can determine its transmission mode and the relay (if necessary). Note that the computational overhead can be neglected as compared to that of communication [22].

Through RTS/CTS handshake, the non-relay neighbors of the source-destination pair will change into sleep state in the remaining time of the current transmission. After finishing data transmission, the source node waits for an acknowledge (ACK). If the destination has successfully receives the packet, it replies with an ACK after the Short Inter-Frame Space (SIFS). Otherwise, the channel keeps silence during this interval. The relay node learns that the intended link fails and can help to relay the data packet. An additional SIFS is added for waiting the relay node to reply an ACK to the source for notifying the availability of transmission cooperation, and the source can change into sleep state in the process of the relay transmission. This is the difference between our scheme and standard CSMA. In case that the relay node doesn't reply the ACK, the source node will finally infer that the relay node fails to overhear the data packet and start a new transmission for this data packet.

4. Performance Evaluation

In this section, we present simulation results of our scheme. The parameters are the same with those in Section 3.1, while $R = 19.2$ kbps, $L = 256$ bytes, $0 < \mu < 1$, $10 < r_{sd} < 250$, $SIFS = 10$ μ s and $DIFS = 50$ μ s. Besides, the length of control packet is 8 bytes. We create a multi-hop data transmission scenario, and compare our scheme with the direct and cooperative schemes in terms of energy efficiency and transmission delay.

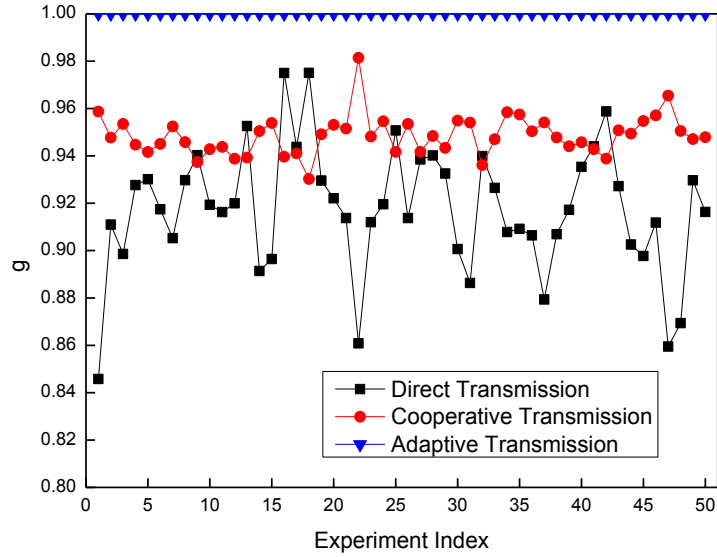


Figure 3. Energy Efficiency Gain in the Multi-hop Transmission Scenario

The result of per-hop energy efficiency gain is shown in Figure 3. We choose our scheme as the baseline for the comparison, and the results of the other schemes have been normalized to that of our scheme. Totally 50 times of experiments are carried out independently.

It can be found from Figure 3 that our scheme outperforms the other two schemes. That is because our scheme is able to determine the best mode for each time of data transmission. Due to the reduction of retransmission times, the cooperative scheme can have higher energy efficiency than the direct scheme in most cases. However, in the scenarios with many short-distance transmission pairs (*e.g.*, the 13th and 16th experiment), the direct scheme are more energy efficient than the cooperative scheme. This observation helps to validate our analysis in Section 3.1.

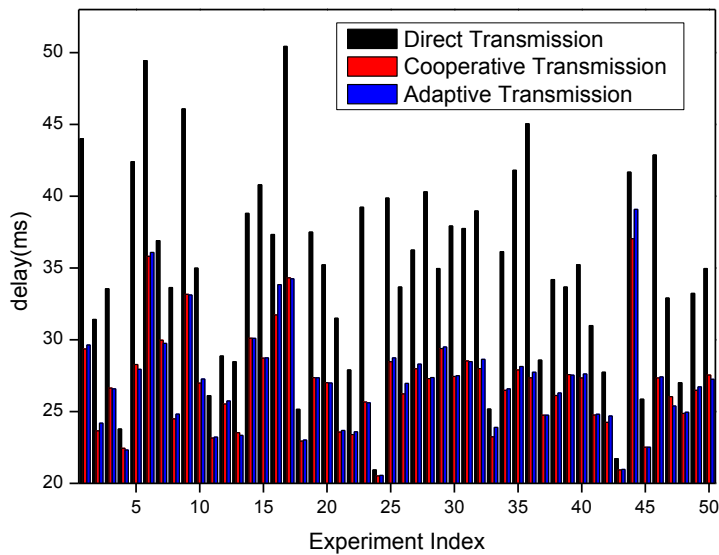


Figure 4. Per-hop Delay in the Multi-hop Transmission Scenario

The result of per-hop data transmission delay is shown in Figure 4. Among the three schemes, the direct scheme has the worst performance. The per-hop delay performance of our scheme is nearly the same with that of the cooperative scheme, although an additional SIFS is added for the ACK from the relay node. This result indicates that our scheme can achieve high energy efficiency with little impact on real-time transmission.

5. Conclusion

In this paper, we present a novel scheme for energy efficient data transmission in WSNs. Through analysis, it is found that cooperative transmission is not always more energy efficient than direct transmission, especially when the length of data packet is small or the source-destination distance is small. Besides, the energy efficiency gain is the best when the relay has equal distance to the source and the destination. Based on these, we design a cross-layer scheme for adaptive transmission, and also evaluate its distinguished performance through extensive simulations.

Acknowledgements

This work was supported in part by the Fundamental Research Funds for the Central Universities of China (No. 2011JBM225), the Science and Technology Foundation of Beijing Jiaotong University (No. 2012RC040).

References

- [1] Z. Zhou, S. L. Zhou, S. G. Cui and J. H. Cui, "Energy-efficient Cooperative Communication in a Clustered Wireless Sensor Network", *IEEE Transactions on Vehicle Technology*, vol. 57, no. 6, (2008), pp. 3618-3628.
- [2] A. Nosratinia, T. E. Hunter and A. Hedayat, "Cooperative Communication in Wireless Networks", *IEEE Communication Magazine*, vol. 42, no. 10, (2004), pp. 74-80.
- [3] J. N. Laneman and G. W. Wornell, "Distributed Space-time-coded Protocols for Exploiting Cooperative Diversity in Wireless Networks", *IEEE Transactions on Information Theory*, vol. 49, no. 10, (2003), pp. 2415-2425.
- [4] H. Ochiai, P. Mitran, H. V. Poor and V. Tarokh, "Collaborative Beamforming for Distributed Wireless Ad Hoc Sensor Networks", *IEEE Transactions on Signal Processing*, vol. 53, no. 11, (2005), pp. 4110-4124.
- [5] S. Q. Wang and J. N. Nie, "Energy Efficiency Optimization of Cooperative Communication in Wireless Sensor Networks", *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, Article ID 162326, (2010), pp. 1-8.
- [6] S. Biswas and R. Morris, "ExOR: Opportunistic Multi-hop Routing for Wireless Networks", *ACM SIGCOMM Computer Communication Review*, vol. 35, no. 4, (2005), pp. 133-144.
- [7] A. Miu, H. Balakrishnan and C. E. Kosksal, "Improving Loss Resilience with Multi-Radio Diversity in Wireless Networks", *Proceedings of 11th Annual International Conference on Mobile Computing and Networking*, (2005), pp. 16-30.
- [8] P. Liu, Z. Tao, T. Korakis and S. S. Panwar, "CoopMAC: A cooperative MAC for wireless LANs", *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 2, (2007), pp. 340-354.
- [9] J. Liang and Q. L. Liang, "Channel Selection in Virtual MIMO Wireless Sensor Networks", *IEEE Transactions on Vehicle Technology*, vol. 58, no. 5, (2009), pp. 2249-2257.
- [10] H. Dobois-Ferriere, D. Estrin and M. Vetterli, "Packet Combining in Sensor Network", *Proceedings of 3rd ACM Conference on Embedded Networked Sensor Systems*, (2005), pp. 102-115.
- [11] Z. Zhou, S. Zhou, J. Cui and S. Cui, "Energy-efficient Cooperative Communication Based on Power Control and Selective Single-relay in Wireless Sensor Networks", *IEEE Transactions on Wireless Communications*, vol. 7, no. 8, (2008), pp. 3066-3078.
- [12] M. S. Gokturk and O. Gurbuz, "Cooperation in Wireless Sensor Networks: Design and Performance analysis of a MAC protocol", *Proceedings of 2008 IEEE International Conference on Communications*, (2008), pp. 4284-4289.
- [13] H. L. Xu, L. S. Huang, G. Liu, Y. D. Zhang and H. Huang, "Optimal Relay Assignment for Fairness in Wireless Cooperative Networks", *International Journal of Ad Hoc and Ubiquitous Computing*, vol. 11, no. 3, (2012), pp. 42-53.

- [14] G. Brante, M. T. Kakitani and R. D. Souza, "Energy Efficiency Analysis of Some Cooperative and Non-Cooperative Transmission Schemes in Wireless Sensor Networks", IEEE Transactions on Communications, vol. 59, no. 10, (2011), pp. 2671-2677.
- [15] C. Sun and C. Y. Yang, "Energy Efficiency Analysis of One-way and Two-way Relay Systems", EURASIP Journal on Wireless Communication and Networking, vol. 2012, no. 46, (2012), pp. 1-18.
- [16] L. Q. Shi and A. O. Fapojuwo, "Cross-layer Optimization with Cooperative Communication for Minimum Power Cost in Packet Error Rate Constrained Wireless Sensor Networks", Ad Hoc Networks, vol. 10, no. 7, (2012), pp. 1457-1468.
- [17] A. Goldsmith, "Wireless Communications", Cambridge University Press, Cambridge, UK (2005).
- [18] C. Intanagonwiwat, R. Govindan and Deborah Estrin, "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks", Proceedings of 6th Annual International Conference on Mobile Computing and Networking, (2000), pp. 56-67.
- [19] Y. B. Zhang and H. Y. Dai, "Energy-Efficiency and Transmission Strategy Selection in Cooperative Wireless Sensor Networks", Journal of Communications and Networks, vol. 9, no. 4, (2007), pp. 473-481.
- [20] W. W. Fang, F. Liu, F. N. Yang, L. Shu and S. Nishio, "Energy-efficient Cooperative Communication for Data Transmission in Wireless Sensor Networks", vol. 56, no. 4, (2010), pp. 2185-2192.
- [21] G. Q. Mao, B. Fidan and B. Anderson, "Wireless Sensor Network Localization Technologies", Computer Networks, vol. 51, no. 10, (2007), pp. 2529-2553.
- [22] G. J. Pottle and W. J. Kaiser, "Embedding the Internet: Wireless Integrated Network Sensors", Communications of ACM, vol. 43, no. 5, (2000), pp. 51-58.

Authors



Weiwei Fang

Weiwei Fang, BSc (2003), PhD (2010), is now an assistant professor at School of Computer and Information Technology, Beijing Jiaotong University. His current research interests include Wireless Sensor Networks, Distributed Computing and Cloud Data Centers. He has coauthored 1 book chapter and more than 30 papers, and served in the Technique Program Committee of more than 30 conferences and workshops.



Quan Zhou

Quan Zhou received her BSc degree from School of Management, Tianjin Normal University, in 2011. She is now a MSc candidate at School of Economics and Management, Beijing Jiaotong University. Her current research interests include Wireless Sensor Networks and Information Systems.



Zishuo Wang

Zishuo Wang is now a BSc candidate at School of Computer and Information Technology, Beijing Jiaotong University. His current research interests include Wireless Sensor Networks and Cloud Data Centers.



Qiang Liu

Qiang Liu, BSc (2002), MSc (2004), PhD (2007), is now an assistant professor at School of Computer and Information Technology, Beijing Jiaotong University. His current research interests include Wireless Networks and Network Simulation. He has coauthored 1 book and more than 20 papers.