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				5c. PROGRAM ELEMENT NUMBER 611102	
6. AUTHORS Yuanyuan Yang				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
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14. ABSTRACT This project provides a comprehensive solution to achieve high energy efficiency in wireless sensor networks. The following is some research highlights of the project. (1) Proposed a novel energy model for batteries and studied the effect of battery behavior on routing in wireless sensor networks. (2) Introduced the concept of battery-aware connected dominating set (BACDS) and given a distributed algorithm to construct the set. (3) Proposed power scheduling algorithms for densely deployed sensor networks to achieve energy efficiency. (4) Studied two-layered sensor networks and presented an on-line algorithm for finding energy efficient and collision-free polling schedules and load balancing algorithms. (5) Considered					
15. SUBJECT TERMS wireless sensor networks, energy efficiency, data gathering, multiple-input-multiple-output (MIMO) technique					
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Report Title

Energy Efficiency Issues in Wireless Sensors Networks

ABSTRACT

This project provides a comprehensive solution to achieve high energy efficiency in wireless sensor networks. The following is some research highlights of the project. (1) Proposed a novel energy model for batteries and studied the effect of battery behavior on routing in wireless sensor networks. (2) Introduced the concept of battery-aware connected dominating set (BACDS) and given a distributed algorithm to construct the set. (3) Proposed power scheduling algorithms for densely deployed sensor networks to achieve energy efficiency. (4) Studied two-layered sensor networks and presented an on-line algorithm for finding energy efficient and collision-free polling schedules and load balancing algorithms. (5) Considered energy efficient sensor deployment in large scale unattended mobile sensor networks and presented a distributed, adaptive sensor deployment algorithm that maximizes the coverage area and reduces sensor movement. (6) Investigated energy-efficient data gathering in sensor networks with mobile data collectors and designed algorithms for planning the moving path of the mobile collector and balancing traffic load in the network. (7) Introduce multiple-input-multiple-output (MIMO) and space-division multiple access SDMA techniques to the data gathering in sensor networks to optimize the system performance. The research results of the project have been published in 11 journal papers and 26 refereed conference papers.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. Z. Zhang, Y. Yang and M. Zhao, "Enhancing downlink performance in wireless networks by simultaneous multiple packet transmission," accepted for publication in IEEE Transactions on Computers, August 2008.
2. M. Ma and Y. Yang "A novel contention-based MAC protocol with channel reservation for wireless LANs," IEEE Transactions on Wireless Communications, vol. 7, no. 10, pp. 3748-3758, October 2008.
3. M. Zhao, M. Ma and Y. Yang, "Applying opportunistic medium access and multiuser MIMO techniques in multi-channel multi-radio WLANs," accepted for publication in ACM/Springer Mobile Networks & Applications (MONET), 2008.
4. C. Ma, Z. Zhang and Y. Yang, "Battery-aware scheduling in wireless mesh networks," ACM/Springer Mobile Networks & Applications (MONET), vol. 13, pp. 228-241, 2008.
5. Z. Zhang, M. Ma and Y. Yang, "Energy efficient multi-hop polling in clusters of two-layered heterogeneous sensor networks," IEEE Transactions on Computers, vol. 57, no. 2, pp. 231-245, Feb. 2008.
6. M. Zhao, Y. Yang, H. Zhu, W. Shao and V.O.K. Li, "Priority-based opportunistic MAC protocol in IEEE 802.11 WLANs," International Journal of Sensor Networks (IJSNet), vol. 3, no. 2, pp. 84-94, 2008.
7. M. Ma and Y. Yang, "SenCar: An energy efficient data gathering mechanism for large scale multihop sensor networks," IEEE Transactions on Parallel and Distributed Systems, vol. 18, no. 10, pp. 1476-1488, October 2007.
8. C. Ma, Y. Yang and Z. Zhang, "Constructing battery-aware virtual backbones in wireless sensor networks," EURASIP Journal on Wireless Communications and Networking, vol. 2007.
9. M. Ma and Y. Yang, "Adaptive triangular deployment algorithm for unattended mobile sensor networks, IEEE Transactions on Computers, vol. 56, no. 7, pp. 946-958, July 2007.
10. C. Ma and Y. Yang, "Battery-aware routing for streaming data transmissions in wireless sensor networks," ACM/Kluwer Mobile Networks and Applications (MONET), vol. 11, no. 5, pp. 757-767, October 2006.
11. M. Ma, Y. Yang and C. Ma, "Single path flooding chain routing in mobile wireless networks" (invited paper), International Journal of Sensor Networks, vol. 1, no. 1/2, pp. 11-19, 2006.

Number of Papers published in peer-reviewed journals: 11.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

1. M. Zhao, M. Ma and Y. Yang, "Mobile data gathering with space-division multiple access in wireless sensor networks," Proc. of IEEE INFOCOM 2008, Phoenix, Arizona, April 2008.
2. M. Ma and Y. Yang, "Data gathering in wireless sensor networks with mobile collectors," Proc. of 22nd IEEE International Parallel and Distributed Processing Symposium, Miami, FL, April 2008.
3. M. Zhao, M. Ma and Y. Yang, "Mobile data gathering with multiuser MIMO technique in wireless sensor networks," Proc. IEEE Global Telecommunications Conference (GLOBECOM '07), Washington, D.C., Nov. 2007.
4. C. Ma and Y. Yang, "A battery aware scheme for energy efficient coverage and routing in wireless mesh networks," Proc. IEEE Global Telecommunications Conference (GLOBECOM '07), Washington, D.C., Nov. 2007.
5. M. Zhao, M. Ma and Y. Yang, "Applying opportunistic medium access and multiuser MIMO techniques in multi-channel multi-radio WLANs," Proc. IEEE BROADNETS 2007, WIRELESS Communications, Networks and Systems Symposium, Raleigh NC, Sept. 2007.
6. M. Zhao, M. Ma and Y. Yang, "Opportunistic medium access control in MIMO wireless mesh networks," 20th International Teletraffic Congress (ITC-20), Ottawa, Canada, June 2007.
7. M. Ma, C. Ma and Y. Yang, "A cross-layer data gathering scheme for heterogeneous sensor networks based on polling and load-balancing," IEEE Wireless Communications and Networking Conference 2007 (WCNC'07) - Networking Symposium, Hong Kong, March 2007.
8. C. Ma, M. Ma and Y. Yang, "A battery aware scheme for energy efficient coverage and routing in wireless MIMO mesh networks," IEEE Wireless Communications and Networking Conference 2007 (WCNC'07) - Networking Symposium, Hong Kong, March 2007.
9. M. Zhao and Y. Yang, "A joint design of MIMO-OFDM transceiver and power-saving MAC WLANs," IEEE Wireless Communications and Networking Conference 2007 (WCNC'07) - Physical/MAC Symposium, Hong Kong, March 2007.
10. M. Zhao, Z. Zhang and Y. Yang, "Medium access diversity with uplink-downlink duality and transmit beamforming in multiple-antenna wireless networks," Proc. IEEE Global Telecommunications Conference (GLOBECOM '06), San Francisco, CA, Nov. 2006.
11. M. Ma and Y. Yang, "Clustering and load balancing in hybrid sensor networks with mobile cluster heads," Proc. of the Third International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks (QShine), Waterloo, Canada, August 2006.
12. M. Ma and Y. Yang, "SenCar: An energy efficient data gathering mechanism for large scale multihop sensor networks," 2006 International Conference on Distributed Computing in Sensor Systems (DCOSS '06), San Francisco, June 2006.
13. M. Zhao, H. Zhu, W. Shao, V.O.K. Li and Y. Yang, "Contention-based prioritized opportunistic medium access control in wireless LANs," Proc. of IEEE ICC'06 Wireless Ad Hoc and Sensor Networks Symposium, Istanbul, Turkey, June 2006.
14. Z. Zhang and Y. Yang, "Enhancing downlink performance in wireless networks by simultaneous multiple packet transmission," Proc. of 20th IEEE International Parallel and Distributed Processing Symposium (IPDPS '06), Rhodes Island, Greece, April 2006.
15. C. Ma, Z. Zhang and Y. Yang, "Battery-aware router scheduling in wireless mesh networks," Proc. of 20th IEEE International Parallel and Distributed Processing Symposium (IPDPS '06), Rhodes Island, Greece, April 2006.
16. M. Ma, Z. Zhang and Y. Yang, "Multi-channel polling in multi-hop clusters of hybrid sensor networks," Proc. of IEEE GLOBECOM 2005 General Conference, St. Louis, MO, Dec. 2005.
17. C. Ma and Y. Yang, "A prioritized battery-aware routing protocol for wireless ad hoc networks," Proc. of the 8th ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM 2005), October 2005, Montreal, Canada. ACM Press.
18. C. Ma and Y. Yang, "Battery-aware routing for streaming data transmissions in wireless sensor networks," Proc. of IEEE BroadNets 2005 Wireless Networking Symposium, Boston, MA, October 2005.
19. M. Ma and Y. Yang, "A novel contention-based MAC protocol with channel reservation for wireless LANs," Proc. of IEEE BroadNets 2005 Wireless Networking Symposium, Boston, MA, October 2005.

20. Y. Yang and C. Ma, ``Battery-aware routing in wireless ad hoc networks -- part I: energy model," Proc. of the 19th International Teletraffic Congress (ITC-19), Beijing, China, Sept. 2005.

21. C. Ma and Y. Yang, ``Battery-aware routing in wireless ad hoc networks -- part II: battery-aware routing," Proc. of the 19th International Teletraffic Congress (ITC-19), Beijing, China, Sept. 2005.

22. M. Ma and Y. Yang, ``Adaptive triangular deployment algorithm for unattended mobile sensor networks, Proc. of IEEE/ACM International Conference on Distributed Computing in Sensor Systems (DCOSS '05), pp. 20-34, Marina del Rey, CA, June 2005.

23. C. Ma, Y. Yang and Z. Zhang, ``Constructing battery-aware virtual backbones in sensor networks," Proc. of 2005 International Conference on Parallel Processing (ICPP '05), pp. 203-210, Oslo, Norway, June 2005.

24. M. Ma, C. Ma and Y. Yang ``Single path flooding chain routing in ad hoc networks," Proc. of 2005 International Conference on Parallel Processing (ICPP '05), pp. 303-310, Oslo, Norway, June 2005.

25. Z. Zhang, M. Ma and Y. Yang, ``Energy efficient multi-Hop polling in clusters of two-layered heterogeneous sensor networks," Proc. of 19th IEEE International Parallel and Distributed Processing Symposium (IPDPS '05), Denver, CO, April 2005.

26. C. Ma, M. Ma and Y. Yang, ``Data-centric energy efficient scheduling in densely deployed sensor networks," Proceedings of IEEE ICC 2004, pp. 3652-3656, Paris, France, 2004.

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):26

(d) Manuscripts

Number of Manuscripts:0.00

Number of Inventions:

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Zhenghao Zhang	0.25
Ming Ma	0.25
Chi Ma	0.25
Miao Zhao	0.25
Hui Zhang	0.00
FTE Equivalent:	1.00
Total Number:	5

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Yuanyuan Yang	1.00	No
FTE Equivalent:	1.00	
Total Number:	1	

Names of Under Graduate students supported

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in
science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue
to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for
Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to
work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive
scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Chi Ma

Hui Zhang

Total Number:

2

Names of personnel receiving PHDs

NAME

Zhenghao Zhang

Chi Ma

Ming Ma

Total Number:

3

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Major Research Activities and Findings:

Research Activities:

This research focuses on the energy efficiency issues in sensor networks based on a new energy flow model. The objective of this research is to develop a battery-aware and density-aware cross-layer mechanism with dynamic power management that provides a comprehensive solution to achieve high energy efficiency in sensor networks. The following is some highlights of our work during the funding period.

We have proposed a novel energy model for batteries and studied the effect of battery behavior on routing in wireless ad hoc/sensor networks. We propose an on-line computable discrete time analytical model to mathematically model battery discharging behavior. We use the data collected from actual nickel-cadmium battery to evaluate the performance of our model and the results show that it can accurately capture the behavior of battery discharging. Based on this model, we also propose a battery-aware routing (BAR) protocol. By dynamically choosing the nodes with well recovered batteries as routers, and leaving the "fatigue" nodes for recovery, the BAR protocol can effectively recover the node's battery capacity and achieve higher energy efficiency. Our simulation results show that the BAR protocol can increase network lifetime and total data throughput significantly. These results have been published in [4, 9, 13, 17, 23, 25, 26, 28, 29].

A critical issue in wireless sensor networks is to construct energy efficient virtual backbones for routing, broadcasting and data propagating. The Minimum Connected Dominating Set (MCDS) was proposed as a backbone to reduce power dissipation and prolong network lifetime. We have introduced the concept of battery-aware connected dominating set (BACDS) and show that in general the BACDS can achieve longer lifetime than the MCDS when the battery behavior is considered. Then we show that finding a minimum BACDS (MBACDS) is NP-hard and give a distributed approximation algorithm to construct the BACDS. The resulting BACDS constructed by our algorithm is at most $(8+\Delta)$ opt size of an optimal BACDS. The simulation results show that the BACDS constructed by our algorithm can save a significant amount of energy and achieve up to 30% longer network lifetime than the MCDS. These results have been presented at International Conference on Parallel Processing and published in EURASIP Journal on Wireless Communications and Networking, Special Issue on Novel Techniques for Analysis and Design of Cross-Layer Optimized Wireless Sensor Networks [7, 13].

We have also proposed two power scheduling algorithms for densely deployed sensor networks, called dynamic energy efficient scheduling (De²S) and statistical energy efficient scheduling (Se²S), to achieve energy efficiency for different types of sensor applications. Our simulation results show that compared with existing algorithms, De²S can reduce about 61.4% of power consumption at the sensor node level and 43.5% at the

network level. It also adapts well to the spatial distribution of sensing events. These results have been presented at IEEE ICC [33].

We have proposed a contention-free polling protocol and a load balancing algorithm for two-layered heterogeneous sensor networks, based on the energy consumption features of the physical layer, MAC layer and network layer. By introducing some powerful nodes, sensors can be organized into clusters. Each powerful node works as a local data sink and gathers data from sensors in the cluster. We first analyze the power consumption model of IEEE 802.15.4-based transceivers. Based on physical layer features of such low-power, low-rate transceivers, we design a contention-free polling protocol for inner-cluster data gathering, so that packet collision can be avoided. By deactivating the transceivers of sensors which do not need to transmit or receive packets, energy consumption on idle listening can be saved. We also propose a load-balancing algorithm at network layer to maximize the network lifetime by taking into consideration of power consumption features at the physical and MAC layers. We show that the proposed scheme can achieve more than one order of magnitude improvement compared to the existing scheme and reduce the duration of sensor duty cycle by at least 50% under various offered traffic loads. Our results show that the polling scheme can reduce the active time of sensors by a significant amount while sustaining 100% throughput. The results have been presented at IEEE International Parallel and Distributed Symposium and IEEE GLOBECOM and published in IEEE Transactions on Computers [5, 24, 32].

We have presented a novel contention-based medium access control (MAC) protocol, namely, the Channel Reservation MAC (CR-MAC) protocol. The CR-MAC protocol takes advantage of the overhearing feature of the shared wireless channel to exchange channel reservation information with little extra overhead. Each node can reserve the channel for the next packet waiting in the transmission queue during the current transmission. We theoretically prove that the CR-MAC protocol achieves much higher throughput than the IEEE 802.11 RTS/CTS mode under saturated traffic. The protocol also reduces packet collision, thereby saving the energy for retransmission. We evaluate the protocol by simulations under both saturated traffic and unsaturated traffic. Our simulation results not only validate the theoretical analysis on saturated throughput, but also reveal other good features of the protocol. For example, under saturated traffic, both the saturated throughput and fairness measures of the CR-MAC are very close to the theoretical upper bounds. Moreover, under unsaturated traffic, the protocol also achieves higher throughput and better fairness than IEEE 802.11 RTS/CTS. The results have been published at IEEE Broadnets and IEEE Transactions on Wireless Communications [2, 27].

We have also considered energy efficient sensor deployment in large scale unattended mobile sensor networks, such as those for battlefield and environmental monitoring. We presented a distributed, adaptive sensor deployment algorithm that aims at maximizing coverage area and minimizing coverage gap and overlap, by adjusting the deployment layout of nodes close to equilateral triangulations, which is proved to be the optimal layout to provide the maximum no-gap coverage and reduce the moving distance of sensors. The algorithm is applicable to practical environments and tasks, such as working

in both bounded and unbounded areas, and avoiding irregularly-shaped obstacles. In addition, the sensor density can be adjusted adaptively to different requirements of tasks. The results have been presented at the International Conference on Distributed Computing in Sensor Systems and published in IEEE Transactions on Computers [8, 30].

We have investigated using simultaneous Multiple Packet Transmission (MPT) which is a type of multiple-input-multiple-output (MIMO) technique, to improve the downlink performance of wireless networks. With MPT, the sender can send two compatible packets simultaneously to two distinct receivers and can double the throughput in the ideal case. We formalize the problem of finding a schedule to send out buffered packets in minimum time as finding a maximum matching problem in a graph. Since maximum matching algorithms are relatively complex and may not meet the timing requirements of real time applications, we give a fast approximation algorithm that is capable of finding a matching at least $3/4$ of the size of a maximum matching in $O(|E|)$ time where $|E|$ is the number of edges in the graph. We also give analytical bounds for maximum allowable arrival rate which measures the speedup of the downlink after enhanced with MPT and our results show that the maximum arrival rate increases significantly even with very small compatibility probability. We also use an approximate analytical model and simulations to study the average packet delay and our results show that packet delay can be greatly reduced even with very small compatibility probability. The results have been published at IEEE International Parallel and Distributed Symposium and IEEE Transactions on Computers [1, 22].

Opportunistic medium access and MIMO techniques are two effective ways to achieve substantial throughput gain in a multiuser wireless system. We have proposed MAC protocols with opportunistic medium access and multiuser MIMO techniques in multi-channel multi-radio wireless networks to explore the utility of the joint design of these two techniques. Specially, in addition to utilizing multiple channels simultaneously and multiple radio transceivers dynamically, multiuser spatial multiplexing and multiuser diversity are employed in each frequency channel to improve system performance. The key ideas can be summarized as follows. By utilizing ATIM windows as in IEEE 802.11 PSM under the DCF mode, user selection and channel negotiation are conducted between the sender and users via ATIM messages on a common channel. multiuser diversity are employed to opportunistically schedule among multiple candidate users to optimize data transmission. During data exchange, on each frequency channel, the sender can transmit data to two distinct users simultaneously in the downlink with the help of multiuser spatial multiplexing, and two users can concurrently send data to the sender by uplink-downlink duality in the uplink, which creates an extra dimension in spatial domain to further leverage the effect of multiuser diversity and multi-channel gains. We also provide an analytical model to characterize the impact of our protocol on the system throughput and energy efficiency performance. Extensive simulations have been conducted and the results demonstrate that our protocol outperforms existing multi-channel MAC protocols with minimal additional overhead and minor enhancements to IEEE 802.11 PSM. The results have been published in [3, 14, 15, 18, 19].

We have investigated energy-efficient data gathering problem in sensor networks with mobile data collectors. We have proposed a new data gathering mechanism for multihop sensor networks. A mobile data observer, called SenCar, which could be a mobile robot or a vehicle equipped with a powerful transceiver and battery, works like a mobile base station in the network. SenCar starts the data gathering tour periodically from the static data processing center, traverses the entire sensor network, gathers the data from sensors while moving, returns to the starting point, and finally uploads data to the data processing center. Unlike SenCar, sensors in the network are static, and can be made very simple and inexpensive. They upload sensing data to SenCar when SenCar moves close to them. Since sensors can only communicate with others within a very limited range, packets from some sensors may need multihop relays to reach SenCar. We first show that the moving path of SenCar can greatly affect the network lifetime. We then present heuristic algorithms for planning the moving path/circle of SenCar and balancing traffic load in the network. We show that by driving SenCar along a better path and balancing the traffic load from sensors to SenCar, the network lifetime can be prolonged significantly. Our moving planning algorithm can be used in both connected networks and disconnected networks. In addition, SenCar can avoid obstacles while moving. Our simulation results demonstrate that the proposed data gathering mechanism can prolong the network lifetime significantly compared to a network which has only a static observer, or a network in which mobile observer can only move along straight lines. These results have been presented in [6, 11, 12, 16, 20, 21].

We have further adopted space-division multiple access (SDMA) technique to optimize data gathering performance in wireless sensor networks. We equip the mobile collector with two antennas. With SDMA, two distinct compatible sensors may successfully make concurrent data uploading to the mobile collector. We focus on the problem of minimizing the total time of a data gathering tour which consists of two parts: data uploading time and moving time. To better enjoy the benefit of SDMA, the mobile collector may have to visit some specific locations where more sensors are compatible, which may adversely prolong the moving path. Hence, an optimum solution should be a tradeoff between the shortest moving path and full utilization of SDMA. We refer to this optimization problem as mobile data gathering problem with SDMA, or MDG-SDMA for short. We formalize the MDG-SDMA problem into an integer program (IP) and then propose three heuristic algorithms that provide practically good solutions to the problem. Our simulation results demonstrate that the proposed algorithms can greatly reduce the total data gathering time compared to the non-SDMA algorithm with only minimum overhead. The results have been presented at IEEE INFOCOM [10].

Important Findings:

The on-line computable discrete time analytical battery model we proposed has low computational complexity and does not require large look-up tables. It is suitable for on-line battery capacity computation in ad hoc/sensor network routing.

The routing protocol based on the battery model can effectively recover the node's battery capacity and achieve higher energy efficiency. Our simulation results show that the BAR protocol can increase network lifetime and total data throughput by up to 28% and 24%, respectively, compared with previous routing protocols.

The battery-aware connected dominating set (BACDS) can achieve longer lifetime than the MCDS when the battery behavior is considered. The BACDS constructed by our algorithm is at most $(8 + \Delta) \times \text{opt}$ size of an optimal BACDS. The simulation results show that the BACDS constructed by our algorithm can save a significant amount of energy and achieve up to 30% longer network lifetime than the MCDS.

Previous power scheduling algorithms modeled the network traffic as a homogeneous Poisson process. However, we observe that in reality sensing packet traffic in a sensor network is generally heterogeneous. We further show that given either homogeneous or heterogeneous sensing packet traffic, the routing packet traffic in the network is heterogeneous. By using a power scheduling algorithm that is adapt to the heterogeneous traffic and differentiating sensing traffic and routing traffic at the sensor node level, the power consumption at the sensor node level and the network level can be significantly reduced.

A two-layered heterogeneous sensor network where two types of nodes are deployed in the network: basic sensor nodes and cluster head nodes (or actuators) is more energy-efficient than a flat network. The fast on-line algorithm for finding energy efficient and collision-free polling schedules in the multi-hop cluster can reduce energy consumption in idle listening. Our results show that the polling scheme can reduce the active time of sensors by a significant amount while sustaining 100% throughput.

By adjusting the deployment layout of sensor nodes close to equilateral triangulations, the no-gap sensor coverage area is maximized and the moving distance of sensors is minimized. The deployment algorithm is applicable to practical environments and tasks, such as working in both bounded and unbounded areas, and avoiding irregularly-shaped obstacles. In addition, the sensor density can be adjusted adaptively to different requirements of tasks.

The data gathering algorithms we proposed can energy-efficiently collect data in sensor networks with mobile data collectors. A mobile data observer, called SenCar, which could be a mobile robot or a vehicle equipped with a powerful transceiver and battery, works like a mobile base station in the network. SenCar starts the data gathering tour periodically from the static data processing center, traverses the entire sensor network, gathers the data from sensors while moving, returns to the starting point, and finally uploads data to the data processing center. Unlike SenCar, sensors in the network are static, and can be made very simple and inexpensive. They upload sensing data to SenCar when SenCar moves close to them. Since sensors can only communicate with others within a very limited range, packets from some sensors may need multihop relays to reach SenCar. We first show that the moving path of SenCar can greatly affect the network lifetime. We then present heuristic algorithms for planning the moving

path/circle of SenCar and balancing traffic load in the network. We show that by driving SenCar along a better path and balancing the traffic load from sensors to SenCar, the network lifetime can be prolonged significantly. Our moving planning algorithm can be used in both connected networks and disconnected networks. In addition, SenCar can avoid obstacles while moving. Our simulation results demonstrate that the proposed data gathering mechanism can prolong the network lifetime significantly compared to a network which has only a static observer, or a network in which mobile observer can only move along straight lines.

The performance of data gathering scheme can be greatly improved by employing space-division multiple access (SDMA) technique and trading off between the shortest moving path of data collectors and full utilization of SDMA. Our simulation results demonstrate that the proposed scheme can greatly reduce the total data gathering time compared to the non-SDMA algorithm with only minimum overhead.

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