Cooperative Transmission Range Extension for Duty Cycle-Limited Wireless Sensor Networks

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***Abstract*—In this paper, we discuss how cooperative transmission (CT) can provide better services and/or lower the initial cost compared to non-CT in wireless sensor networks. To see the performance of CT and non-CT in both battery operated and energy harvesting networks, we look at the duty cycle instead of the energy and convert the conventional non-CT and CT routing protocols to their duty cycle versions. We calculate the duty cycle limit, which is used as a performance bound in our network simulation, based on a building management application. Through the network simulation, we show that when CT is used appropriately, it allows more sensor nodes to be supported by a single gateway node, thereby lowering initial cost, and it can provide more frequent data gathering.**

I. Introduction

In order for a wireless sensor network to operate for a certain period of time (battery operated sensor network) or continuously (energy-harvesting sensor network), it is essential that the duty cycle of each sensor needs to be kept low, and many duty cycle schemes have been developed. To keep the node inactive as long as possible, duty-cycled MAC schemes that enable communicating nodes to wake up synchronously [1] [2] or asynchronously [3] [4] have been proposed. Adjusting the duty cycle based on the available energy or data has been proposed in [5] and [6]. This paper takes a different approach, based on the assumption that *if* nodes can operate at a certain duty cycle, they will have continuous operation with energy harvesting, or they will have the desired lifetime with battery operation. Under this assumption, the goal becomes to satisfy service requirements while meeting this duty cycle constraint. Even with the help of the duty cycle MAC schemes [1] [2] [3] [4] or with duty cycle adaptation [5] [6], there are many cases that network cannot meet the service requirements. In this paper, we compare two protocols, one that uses cooperative transmission, and one that does not, in terms of their ability to meet both the service requirement for a building management application as well as the duty cycle constraint or limit for all nodes in the network.

The usual way to assess the lifetime or the performance of an energy constrained or energy harvesting wireless sensor network, for a given protocol, is to simulate or analyze the protocol, assuming a certain node energy consumption model and a certain energy harvesting model. Disregarding cycle-life limitations, as long as the harvesting rate exceeds the consumption rate, a node can operate continuously. We observe that the energy related parameters can be converted to the duty cycle related values. That is, the amount of time that a node is active is proportional to the energy consumed for the node. This means the energy related parameters required for performance evaluations in the simulation can be converted to i) the duty cycle limit and ii) the duty cycle of a node. Therefore, once we get the duty cycle limit, the network simulation can be greatly simplified because we only have to measure the duty cycle of each node, without applying any energy related models, and see if all nodes conform to the limit. This approach is particularly useful when we deal with the energy-harvesting network because we can remove both harvesting operations and energy consumptions from the simulation. Therefore, in this paper, we use this duty cycle limit concept to understand the performance of the routing protocols especially under the energy harvesting environment, and we expect the simulation results that we provide in this paper to be similar to the results obtained from the actual energy harvesting network simulations. Note that when the duty cycle limit can be obtained and if all the nodes can meet this limit, then a continuous service is guaranteed for the desired duration of the network. If any of the nodes do not meet the limit, the service is compromised.

The routing protocols that we compare in this paper are one that uses cooperative transmission (CT) [7] and a conventional one that does not use CT. Instead of using one transmitting node in a communication link, CT uses multiple transmitting nodes to combat multi-path fading and shadowing. The cooperative diversity gain obtained from CT gives an SNR advantage over the conventional non-CT communication, and this advantage can be used to reduce the transmit power, increase the data rate, or extend the range. Here we use CT's range extension feature and show that when CT is used appropriately (in a way to balance the duty cycle across the network), the nodes in the network can meet the duty cycle limit even in a situation that the non-CT approach cannot, thereby giving more options (larger network, more sensors per gateway, and more frequent data reporting period) to the network operators. Some authors have discussed the range extension of CT in [8], [9] and [10]. In this paper, we convert

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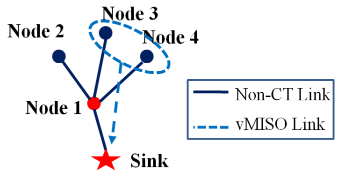


Fig. 1. CT vs. non-CT.

the work in [10] to the duty cycle version and see the benefit of CT.

This paper is organized as follows. Section II briefly explains how CT can have better performance in meeting the duty cycle limit. The method of calculating the duty cycle limit is discussed in Section III. How a conventional routing scheme can be converted to the active-time-aware routing so that we can eliminate the energy related parameters is introduced in Section IV. Section V shows the network simulation results and concluding remarks are provided in Section VI.

II. Using CT to meet the duty cycle limit

Consider the example in Fig. 1 where there is a Sink, one node (Node 1), which is one hop away from the Sink, and three nodes (Nodes 2, 3 and 4), which are each two hops away from the Sink and one hop away from Node 1. Here, the hop count is based on the range when non-CT is used. To simplify the analysis, let us assume that i) at any point in time, each node is either transmitting, receiving, or sleeping, and ii) there is a way for the receiving and transmitting nodes to wake up when the communication is required between them. Let the transmit time be T_{TX}, the receive time be T_{RX}, and T = T_{TX} = T_{RX}. Also consider the application that every node in the network must report its data periodically, and this *report period* is denoted as T_{RP}. If the duty cycle limit is $5T/T_{RP}$, we can easily see that Node 1 violates the limit because it spends $7T$ (T for sending its own data, $3{\times}2T$ to relay the data for Nodes 2, 3 and 4) during the period T_{RP}, whereas Nodes 2, 3 and 4 spend only T.

Now consider the case when CT is used to extend the range in a way to reduce the duty cycle of Node 1 by not using the Node 1, but using Nodes 3 and 4 cooperatively to extend the range and communicate directly with the Sink, the concept we have used in [10]. If Nodes 3 and 4 can communicate directly with the Sink when they cooperate, then Node 1 does not have to relay the data, and Node 1 now spends $3T$ (relaying for Node 2 only) whereas Nodes 3 and 4 each spend $4T$ (T for sharing the message, T for sending its data cooperatively to the Sink, $2T$ for receiving and sending other node's data cooperatively), thereby meeting the duty cycle limit.

From the simple example above, we can see that CT has a possibility of supporting a larger network and more frequent service compared to non-CT. Note that meeting the duty cycle limit means continuous success in delivering the required service, and if this limit cannot be met, the service will not last for the desired duration (in the battery operated sensor network) or it will be suspended from time to time (in the energy-harvesting sensor network). Therefore, if any node in the network exceeds the duty cycle limit, the service is compromised and the network fails to do its purpose.

III. Obtaining the Duty Cycle Limit

Since the duty cycle limit varies depending on the application and service requirement, we need to specify the target application. The target application for this paper is the building management application which uses sensors with energy harvesting capabilities, where indoor light is the energy source. As mentioned earlier, each node has to report data periodically. Also, each node uses a fixed transmit power. The reporting is assumed to be well scheduled so that there is no collision. Since we are particularly interested in comparing the network protocols, we do not specify the MAC layer protocol, although we include acknowledgement (ACK) packet cost in the duty cycle limit calculation. We therefore do not specify the underlying duty cycle scheme ([1]-[4]), and since the overheads of the duty cycle scheme are missing, the duty cycle limit presented in this section is calculated assuming an ideal duty cycle method and this value can be considered as the maximum bound of the duty cycle limit. The ideal duty cycle method that we assume has i) negligible overheads for sleep/wake up scheduling and ii) capability of making communicating nodes be active only for the data transmit/receive period and startup period.

With the above assumptions and conditions, the duty cycle limit can be obtained as follows. Suppose we can get the harvested energy (for each node), E_{EH}, over T_{RP}. During T_{RP}, a node must consume i) the energy for sensing and transmitting, denoted as E_{ST}, and ii) the energy while sleeping, denoted as E_{Sleep}. E_{EH} - E_{ST} - E_{Sleep} gives the available energy that each node can use for relaying the packets of other nodes. Therefore, if we divide the available energy value by the power consumption for relaying denoted as P_{Relay}, we get the maximum time a node can spend for relaying (operations of CT relaying and non-CT relaying are same because they both involve receiving and transmitting). Finally, if we divide the relaying time by T_{RP}, we get the duty cycle limit for relaying, which will be denoted as D_{Relay}. In symbols, D_{Relay} can be expressed as

$$D_{Relay} = \frac{E_{EH} - E_{ST} - E_{Sleep}}{P_{Relay} \times T_{RP}}. \tag{1}$$

E_{ST} can be obtained from $E_{ST} = E_{Data}^{TX} + E_{Ack}^{RX} + E_{Init} + E_{Sen}$ where E_{Data}^{TX}, E_{Ack}^{RX}, E_{Init}, and E_{Sen} are the energy consumptions for data transmission, acknowledgment receiving, board initialization, and sensing, respectively. From now on, we use P and T for the power and time values respectively corresponding to the energy value E. For example, the power and time values for E_{Data}^{TX} are denoted as P_{Data}^{TX} and T_{Data}^{TX}, respectively. For relaying, a node has to send and receive both a data and an ACK, and it spends time for the board initialization. Therefore, P_{Relay} = $(E_{Data}^{TX} + E_{Data}^{RX} + E_{Ack}^{TX} + E_{Ack}^{RX} + E_{Init})$/$T_{Relay}$ where T_{Relay}= $T_{Data}^{TX} + T_{Data}^{RX} + T_{Ack}^{TX} + T_{Ack}^{RX} + T_{Init}$. For E_{Sleep}, we use $E_{Sleep} = P_{Sleep} \times T_{RP}$.

TABLE I
POWER AND TIME VALUES [11].

Power (mWatt)		Time (msec)	
P^{TX}_{Data} = 131.4	P_{Init} = 20	T^{TX}_{Data} = 35	T_{Init} = 20
P^{RX}_{Data} = 174.3	P_{Sen} = 53.3	T^{RX}_{Data} = 35	T_{Sen} = 7.5
P^{TX}_{Ack} = 111.1	P_{Sleep} = 0.054	T^{TX}_{Ack} = 0.45	
P^{RX}_{Ack} = 133.3		T^{TX}_{Ack} = 0.45	

The reason why T_{RP} is used instead of the sleep mode time T_{Sleep} is as follows. When the indoor light is the energy source, the duty cycle should be very low, which is presented in [11]. Based on this fact, the maximum active mode time is negligible when compared to T_{RP}, so T_{Sleep} and T_{RP} can be considered approximately equal, and $E_{Sleep} = P_{Sleep} \times T_{RP}$ can be used for the simplification.

In order to get the required energy values, we use [11] where the measurements are obtained using Tyndall motes with Sensirion SHT71 temperature/humidity sensor and Analog Devices ADXL250 dual axis accelerometer[1] are used. We summarize the power and time values in Table I. E_{EH} can be obtained from [12], which is $E_{EH} = (P_{PV} \times \eta_{MPPT} - P_{Leak}) \times \eta_{SR} \times T_{RP}$, where $P_{PV} = 382\mu W$ is the maximum output of a Sanyo AM1815 solar panel under 500 Lux fluorescent light, $\eta_{MPPT} = 90.5\%$ is the maximum power point tracker efficiency, $P_{Leak} = 35\mu W$ is the average leakage power of Maxwell BCAP0005 supercapacitor, while $\eta_{SR} = 51\%$ is the average conversion efficiency of TI TPS61220 switching regulator.

IV. CONVERTING PROTOCOLS

As we have mentioned in the introduction, the duty cycle of a node is closely related to the energy consumption. In this section, we introduce how the existing energy-aware routing protocols can be changed to their duty cycle versions, which will be referred to as *active-time-aware* routing protocols. Note that the active-time-aware routing protocol should not be considered as a new routing method; rather it should be considered as the conventional routing being looked at from a different angle (the active time instead of the energy). This enables us to simplify the simulation by eliminating the energy related parameters.

In the following subsections we provide the methods of doing active-time-aware routing for both non-CT and CT, which we use in our simulations.

A. Converting an Energy-Aware-Routing Protocol

Conventional energy-aware routing protocols [13] [14] [15] try to use the nodes with high residual energies while minimizing the total energy consumption. Since we have assumed a fixed transmit power in Section III, the energy consumption of transmitting a packet for each node is same and it follows that an energy-aware routing protocol needs only to account for the residual energy in the routing decision. When all nodes have equal initial energy at the beginning, the node that has been more active will have less residual energy. Therefore, the route that gives the smallest accumulated active time contains the nodes with the highest total residual energy. Therefore, the active-time-aware non-CT routing protocol uses each node's accumulated active time as a cost metric, and finds the smallest cost path to the destination.

B. Converting the REACT Protocol [10]

For the CT case, we modify the REACT Protocol in [10], where the CT is triggered based on the residual energy of nodes. In the active-time-aware case, a node that has a packet to send tries to do CT when the next node's accumulated active time is larger than its accumulated active time value (instead of residual energy value in [10]). Also, the cooperating node selection of the REACT protocol can be simplified because the only cost we consider is the active time. Instead of calculating the mean residual energy of its neighbors and selecting cooperating nodes based on how their residual energy compares to the mean, the leader node that wants to do CT calculates the mean accumulated active time of its neighbors and compares it to the accumulated active time of each candidate cooperator. The detailed process of doing active-time-aware CT is summarized below, which is just a simplified version of the REACT protocol.

Following [10], we denote the transmitting node in a non-CT link as n_{TX}, and the receiving node as n_{RX}. The accumulated active time of node n_i will be denoted as $T(n_i)$. We define the set of nodes containing all cooperators as S_{CT} and the total number of cooperators as N_c. The maximum number of the orthogonal diversity channels will be denoted as N_d, and N_c should satisfy $2 \leq N_c \leq N_d$. The maximum transmission range of a single node will be denoted as $d^{\text{max}}_{\text{tx}}$. d_{req} in [10] is still used, but it will only be used to check if cooperation is possible, and all nodes use the same transmit power as assumed. The average accumulated active time value, T^{avg}, is calculated considering the leader and all its neighbors.

Following [10], the conditions used for CT are

$$T(n_i) \leq min(T^{\text{avg}}, T(n_{\text{RX}})), \quad (2)$$

and

$$d_{\text{req}} \leq d^{\text{max}}_{\text{tx}}. \quad (3)$$

When a source node needs to transmit the data to the Sink, it first establishes a primary route using a conventional non-CT routing protocol. Then, along the primary route, when n_{TX} needs to transmit/relay the packet, it decides whether to do CT or not using the following procedure.

- **Step 1.** n_{TX}, the leader, checks the active time of n_{RX}, and if $T(n_{\text{TX}}) < T(n_{\text{RX}})$, n_{TX} calculates T^{avg}. Otherwise, decide to do non-CT and exit this procedure.

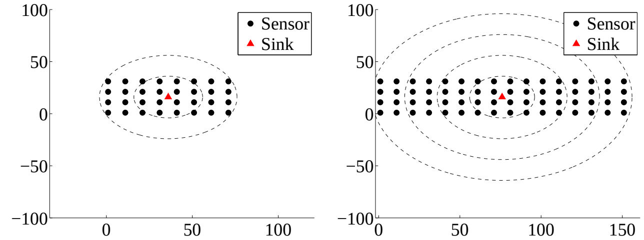
[1]In the building management, the accelerometer can be used for monitoring the ventilating unit. Note that in this application, the accelerometer is not required to be powered all the time. The ventilating units use a so called "bang bang (on/off) control," and they can operate for any pre-set period of time, which can be set to be the report period (T_{RP}). Therefore, the sensor node only needs to wake up every T_{RP} to detect the on/off states.

- **Step 2.** From its neighbors, n_{TX} decides possible cooperators (excluding n_{TX}) satisfying the condition in (2), and saves those nodes in the set S_{p}. If S_{p} is empty, decide to do non-CT and exit this procedure. Otherwise, set N_c=2 and proceed to the next step.
- **Step 3.** If $|S_{\text{p}}| \geq N_c$, the node n_{TX} forms the set S_{CT} ($|S_{\text{CT}}| = N_c$) by picking up $N_c - 1$ nodes from the set S_{p} that have the lowest active time and itself. If $|S_{\text{p}}| = N_c - 1$, $S_{\text{CT}} = \{n_{\text{TX}}, S_{\text{p}}\}$. Otherwise, decide to do non-CT and exit this procedure.
- **Step 4.** Calculate d_{req} (in [10]) for the nodes in S_{CT}. Check the condition in (3). If (3) holds, decide to do CT and exit this procedure. If (3) does not hold, set $N_c = N_c + 1$ and if $N_c \leq N_d$ go to Step 3. If $N_c > N_d$, decide to do non-CT and exit this procedure.

V. Simulation Results

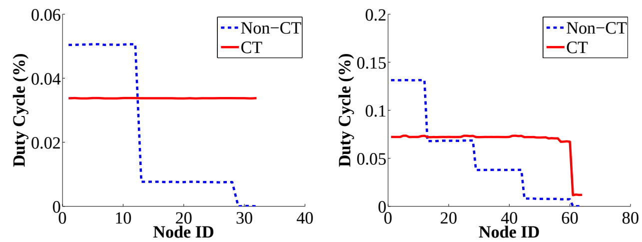
For the physical layer, we assume a Rayleigh fading channel and log-normal shadowing with the shadowing standard deviation of 5dB and the path loss exponent of 2.9 [16]. The fading channel is slowly varying and remains same for the entire virtual MISO transmission (CT). We assume that the orthogonal diversity channel is obtained by a space-time block code (STBC), and the maximum number of orthogonal channels is 4. Also, the modulation scheme is assumed to be BPSK. We obtain i-th order cooperative diversity gain, $\gamma_{\text{div},i}$ for the Rayleigh fading channel with log-normal shadowing using Monte Carlo simulation. We calculate $\gamma_{\text{div},i} = \gamma_1 - \gamma_i - 10\log_{10}(i)$, where $i > 1$ is the diversity order and γ_i is the average SNR (in a single diversity channel, in dB) required to achieve a bit error rate (BER) of 10^{-3}, when CT is used. γ_1 ($> \gamma_i$) is the required SNR without CT, and $10\log_{10}(i)$ is the array gain in dB. From Monte Carlo simulations for BER, the diversity gain values that we get are 7.5, 9.23, and 9.98 (in dB) for N_c = 2, 3 and 4 respectively, and these values are used for the protocol simulation. The maximum transmission range of a node, $d_{\text{tx}}^{\text{max}}$, is assumed to be 20m.

We compare the non-CT routing protocol (Section IV-A) with the CT routing protocol (Section IV-B). The simulation uses the assumptions and conditions that have been made in Section III. Each node in the network sends a packet to the Sink every T_{RP}, and the time values in Table I are used to calculate the active time of each node. To follow the assumption in Section III that the reporting is well scheduled to have no collision, only one node sends its packet and no other nodes send their packets until the packet reaches the Sink. The order of transmissions is based on the Node ID; Node 1 followed by Node 2, and so on. In Section III, we derived the duty cycle limit for relaying (D_{Relay}). Therefore, we measure the duty cycle of each node for *relaying* by considering the amount of the time the node is active excluding the time spent for initial sensing and transmitting when the node is a source. The duty cycle limit is calculated using (1) and the values in Table I. The simulation is done once and it runs for 24 hours (in simulation time). We measure each node's accumulated active time and get the duty cycle of each node.



(a) 4×8 network. The smallest. (b) 4×16 network. The largest.

Fig. 2. The network topology.

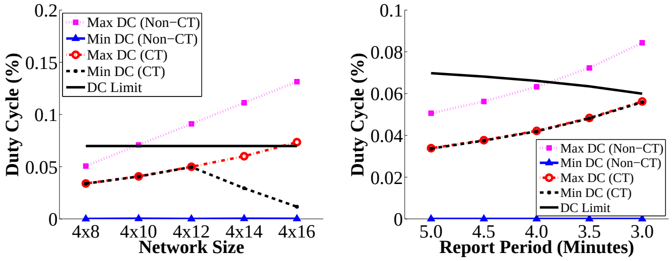


(a) 4×8 network. (b) 4×16 network.

Fig. 3. The duty cycle of all nodes for both non-CT and CT.

We consider a square-grid network with 10m minimum node spacing. The two network sizes we consider are 4×8 and 4×16, as illustrated in Fig. 2. We have chosen the strip-shaped network because it closely resembles the deployment of the building management application. The Sink is located at the center of the network, and the Node ID of a node is assigned according to the proximity of the node to the Sink (the node closer to the Sink gets lower Node ID). The dashed ovals in Fig. 2 indicate how many hops away is a node from the Sink, if non-CT is used. The report period, T_{RP}, is assumed to be 5 minutes, and the duty cycle limit, D_{Relay}, is 0.0698%.

Fig. 3 shows simulation results of the duty cycle achieved by each node in the network, for both sizes of networks. In the case of the 4×8 network (Fig. 3a), the non-CT scheme has a relatively large difference in duty cycle between nodes, whereas in the case of CT, it can be observed that the duty cycles of all the nodes are almost equal, at about 0.034%. In the case of non-CT, the nodes close to the Sink (nodes with low Node IDs) have to spend their time relaying other nodes data, and the nodes far away from the Sink do not have to relay the data, giving the nodes farthest away from the Sink the duty cycle value of zero (zero because we exclude the time for the initial sensing and transmitting in our active time measurements). CT has the option to use the nodes far away from the Sink to cooperate with each other to directly communicate with the Sink and, by balancing instances of CT and by choosing the cooperators wisely as in [10], the duty cycles of the nodes are well balanced. Fig. 3b shows the case of the 4×16 network, where we can observe that CT fails to perfectly balance the duty cycle. This happens because the nodes far away from the Sink are not used as cooperators most



(a) Different network sizes.

(b) Different report periods

Fig. 4. The maximum and minimum duty cycles of non-CT and CT.

of the time because using them will not give sufficient range extension to communicate directly with the Sink.

More important than balancing the duty cycle is for each node to have a duty cycle less than the duty cycle limit. Fig. 4a shows the maximum and minimum duty cycle values for both non-CT and CT along with the duty cycle limit for 5 different network sizes, 4×8 (Fig. 2a), 4×10, 4×12, 4×14, and 4×16 (Fig. 2a) with the Sink located at the center of the network and T_{RP} = 5 minutes. As the network size grows, the maximum duty cycle increases because there are more data to be transmitted within the report period. As can be seen from the figure, non-CT can only meet the duty cycle limit when the network size is 4×8 (For 4×10, max DC (non-CT) is 0.0709%) whereas CT can support up to 4×14 without violating the limit. In other words, CT can support a larger network without compromising the required services and lifetime.

Fig. 4b shows the impact of the report period. Here we fix our network to be 4×8, and reduce the report period by 0.5 minutes starting from 5 minutes until it reaches 3 minutes. Note that, unlike the case of the different network sizes, reducing the report period decreases the duty cycle limit, because of more frequent data transmission[2]. As can be seen from the figure, CT not only balances the duty cycle as the report period decreases but also meets the duty cycle limit up to 3 minutes, which is more frequent reporting than the 4 minutes that non-CT can support. This means that when CT is used, the data gathering can be done more frequently while meeting the duty cycle limit, compared to non-CT.

Although we have targeted and simulated the energy harvesting network case, if one can get the duty cycle limit for the battery operated network, which is not provided in this paper, the performance of the battery operated network can also be measured using the simulation method that we have discussed in this paper.

VI. Conclusion

In this paper, we have discussed how cooperative transmission (CT), when it is used for range extension, can balance the duty cycles of the nodes in a wireless sensor network. The duty cycle limit was computed for a building energy application, assuming the energy harvesting from indoor light. Under these conditions and 5 minutes of reporting period, the CT protocol was shown to support a 75% larger network, compared to the non-CT protocol. Alternatively, for a 32-node network, CT was shown to support more frequent reporting of sensors, specifically every 3 minutes vs. every 4 minutes, while maintaining continuous operation with energy harvesting. The same approach can also be used to minimize and equalize the duty cycles of nodes in a battery-driven wireless sensor network.

[2]Although (1) seems to indicate that D_{Relay} is inversely proportional to T_{RP}, it is actually proportional to T_{RP} once you apply $E_{EH} = P_{EH} \cdot T_{RP}$ and $E_{Sleep} = P_{Sleep} \cdot T_{RP}$ to (1).

References

[1] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *Proc. IEEE INFOCOM*, 2002.

[2] T. van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," in *SenSys*, 2003.

[3] J. Polastre, J. Hill, and D. E. Culler, "Versatile low power media access for wireless sensor networks," in *SenSys*, 2004.

[4] M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-MAC: A short preamble MAC protocol for duty-cycled wireless networks," in *SenSys*, 2006.

[5] J. Hsu, S. Zahedi, A. Kansal, M. Srivastava, and V. Raghunathan, "Adaptive duty cycling for energy harvesting systems," in *Proc. IEEE ISLPED'06*, Oct. 2006.

[6] P. Boonma, P. Champrasert, and J. Suzuki, "A biologically inspired architecture for self-managing sensor networks," in *Proc. IEEE SECON*, 2006.

[7] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3063–3080, Dec. 2004.

[8] 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," *IEEE Trans. Mobile Comput.*, vol. 6, no. 6, pp. 579–594, 2007.

[9] S. Lakshmanan and R. Sivakumar, "Diversity routing for multi-hop wireless networks with cooperative transmissions," in *Proc. IEEE SECON*, 2009.

[10] J. W. Jung and M. A. Ingram, "Residual-energy-activated cooperative transmission (REACT) to avoid the energy hole," in *Proc. IEEE ICC 2010 Workshop on Cooperative and Cognitive Mobile Networks*, May 2010.

[11] C. Ó Mathuna, T. O′Donnell, R. Martinez-Catala, J. Rohan, and B. O′Flynn, "Energy scavenging for long-term deployable mote networks," *The International Journal of Pure and Applied Analytical Chemistry*, vol. 75, no. 3, pp. 613–623, 2008.

[12] W. S. Wang, T. O′Donnell, N. Wang, M. Hayes, B. O′Flynn, and C. Ó Mathuna, "Design considerations of sub-mW indoor light energy harvesting for wireless sensor systems," *ACM Journal on Emerging Technologies in Computing Systems (JETC)*, vol. 6, no. 2, 2010.

[13] K. Kar, M. Kodialam, T. V. Lakshman, and L. Tassiulas, "Routing for network capacity maximization in energy-constrained ad-hoc networks," in *Proc. IEEE INFOCOM*, 2003.

[14] J.-H. Chang and L. Tassiulas, "Maximum lifetime routing in wireless sensor networks," *IEEE/ACM Trans. Networking*, vol. 12, no. 4, pp. 609–619, Aug. 2004.

[15] Q. Li, J. Aslam, and D. Rus, "Online power-aware routing in wireless ad-hoc networks," in *Proc. MobiCom*, July 2001.

[16] H. Jung, Y. J. Chang, and M. A. Ingram, "Experimental range extension of concurrent cooperative transmission in indoor environments at 2.4GHz," in *IEEE Military Communications Conference (MILCOM)*, 2010.