# An Evaluation of Cooperation Transmission Considering Practical Energy Models and Passive Reception

Jin Woo Jung*, Aravind Kailas*, Mary Ann Ingram*, and Emanuel Mihai Popovici**

*School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, 30332-0250, USA
**Dept. of Microelectronic Engineering, National University of Ireland, Cork, Ireland

***Abstract*—The total energy consumed by the radios is compared for a cooperative transmission (CT) protocol and a non-CT routing protocol, in a two-hop, single cluster, ad hoc network. The radio energy model is a function of parameter sets that are typically found in radio specifications. The protocols are compared for five different parameter sets, corresponding to five different existing radios. The CT protocol is the Opportunistic Large Array (OLA). The non-CT protocol simply selects one node from the cluster to forward the packet, but other nodes in the cluster that do not relay are assumed to overhear or decode at least part of the packets. The relative energy consumption is determined as a function of the fraction of the data packet that is decoded by the node for decision-making. CT is shown to be beneficial for certain decoding fractions and for certain radio parameter sets.**

***Index Terms*—Cooperative Transmission, Energy Models, Wireless Sensor Networks**

## I. Introduction

With the emergence of miniaturized radios and miniaturized sensors [1], there has been significant interest in energy-efficient communication protocols for Wireless Sensor Networks (WSNs). Cooperative Transmission (CT) has been considered as an energy-saving technique for WSNs because it provides diversity gain. Exactly how this gain saves energy in networks is a question drawing much recent attention [3]-[10]. However, these works consider mainly the physical layer and do not consider practical output powers. This paper investigates the benefits of CT for values of output power and circuit energy consumption that are consistent with radios available today and considers the energy consumption of passive nodes that decode at least the medium access control (MAC) headers but do not relay.

Many authors have considered how CT reduces transmission energy [3]-[7]. Others have included energy consumed in the electronic circuitry for both transmission and reception [8]-[10]. For example, when considering a single virtual Multiple-Input-Multiple-Output (MIMO) transmit diversity link, the authors in [8] found that circuit energy costs dominate at short ranges making a Single-Input-Single-Output (SISO) link preferable when constellation size is fixed and the CT gains are used just to lower per-node transmit powers. However, if the CT gains are instead used to increase the constellation size, then circuit power costs can be reduced enough through packet shortening to give CT the advantage, even at short ranges [8]. [9] and [10] extend the results of [8]; [10] includes the increased training costs for higher-order constellations (minor effect) and increased path loss exponents (major effect), and [9] shows that cooperation is advantageous when the inter-node distances are comparable to the source-destination distances, and advocates decode-and-forward as the best strategy in terms of energy-efficiency. Because these previous works evaluate CT benefits in terms of distance and not power, it is not clear if the powers required are consistent with today's radio technology. We attempt to address this question in the present paper by evaluating the CT energy benefit for node power and energy models that are consistent with several existing radios. Also, considering that popular sensor radios today do not do rate adaptation (e.g. the MICAz radio CC2420 [11]), and to simplify our analysis, we return in this paper to the constant rate case (i.e. fixed constellation).

Since reception energy costs are significant in WSNs, another quantity that should be considered when comparing routing protocols is the reception energy costs of passive nodes that decode at least part of the packet even though they are not the designated relay or the destination. Therefore another contribution of this paper is an evaluation of how the energy consumption of the passive nodes impacts the CT and non-CT comparison.

## II. Network Model

We consider a simple two-hop static network, which has a Source, $N_c$ half-duplex relays ($N_c \geq 2$) in a single cluster of "intermediate nodes," and a Destination as shown in Fig. 1. We assume a node can successfully decode-and-forward a packet without error when its received signal-to-noise ratio (SNR) is greater than or equal to a modulation-dependent threshold. We assume that all the $N_c$ relays are randomly distributed within the intersection of the decoding regions of the source and destination, which we refer to as the "overlap region". Further, we impose that direct transmission from the source to the destination is not possible. We also assume that the

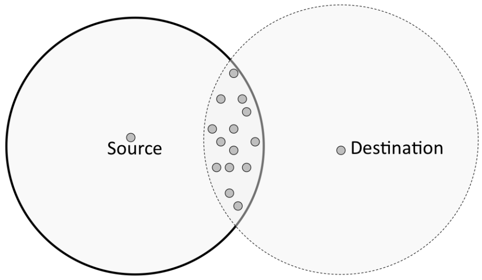


Fig. 1. The network model. The large circles indicate the decoding ranges of the source and destination.

$N_c$ nodes are densely distributed, enabling them to cooperate and relay the packet to the destination. Among cooperation strategies [12], we focus on radiated power reduction while keeping constant the BER at the destination.

Since we assume the node locations are static, we do not consider route setup costs in this paper.

## III. Total Energy Consumption for CT- and non-CT-based Protocols

In this section, we derive the total energy consumed by the nodes for cooperative and non-cooperative transmission-based protocols. To evaluate the energy requirements of CT, we consider a simple form of CT called the Opportunistic Large Array (OLA) [2]. An OLA is a set of nodes that transmit the same message at approximately the same time. They do this without coordination between each other (almost no overhead for broadcast applications), but they naturally fire at approximately the same time in response to energy received from a single source or another OLA. For the network model described in Section II, an OLA comprises $N_c$ nodes. We will consider the energy consumption of only the intermediate nodes, since only they cooperate. This is consistent with the assumption that either there are no other nodes besides the ones in Fig. 1 or that the other nodes are sleeping and consume negligible energy.

Let $E_{\text{rad}}$ be the energy radiated by the relay node in a direct transmission to the destination node when it relays one data packet. Also, let $E_{\text{tx}}$ and $E_{\text{rx}}$ denote the energies expended in the electronics when the relay node transmits (not including $E_{\text{rad}}$) and receives one data packet, respectively.

The energy expended by one relay node to receive and relay when an OLA scheme is used, $E_{\text{node, c}}$, is

$$E_{\text{node, c}} = E_{\text{rx}} + E_{\text{tx}} + \frac{E_{\text{rad}}}{N_c G_{\text{div}}(N_o)}, \tag{1}$$

where $N_o$ is the number of orthogonal dimensions or diversity channels of the signal received at the destination and $G_{\text{div}}(N_o)$ is the diversity gain, which is amount of the fade margin that can be reduced without diminishing the error rate of the link [13].

The total energy consumed by an OLA transmission is the total energy consumed by all the cooperators, i.e., $N_c E_{\text{node, c}}$. Hence the total energy consumed in the case of OLA is

$$E_{\text{total, c}} = \underbrace{N_c E_{\text{rx}} + N_c E_{\text{tx}} + \frac{E_{\text{rad}}}{G_{\text{div}}(N_o)}}_{N_c \text{ cooperators}}. \tag{2}$$

In the case of a non-cooperative transmission (non-CT) protocol, only one node out of $N_c$ intermediate nodes will relay the packet to the destination. We refer to the other nodes as "passive" nodes. It is noted that even with the route having been established and the relay node chosen, the remaining $N_c - 1$ passive nodes are not free from overhearing. Based on our network model described in Section II, $N_c - 1$ nodes listen to the source-originating transmissions (first hop), and possibly, also to the relay-originating transmissions (second hop). However, it is possible that these passive nodes decode only the header in the received data packet and then turn their circuits off at least for the duration of the data packet. Therefore, if we define $\rho$ as the fraction of the data packet that is decoded by every node in order to make a decision on packet forwarding, and $n_{\text{oh}}$ as number of overhearing, then $n_{\text{oh}} \rho E_{\text{rx}}$ is the energy consumed by the passive nodes. Note that $N_c - 1 \leq n_{\text{oh}} \leq 2(N_c - 1)$. The total energy consumed in the case of a non-CT protocol is

$$E_{\text{total, nc}} = \underbrace{E_{\text{rx}} + E_{\text{tx}} + E_{\text{rad}}}_{\text{Selected relay node relays}} + \underbrace{n_{\text{oh}} \rho E_{\text{rx}}}_{\text{Overhearing}}. \tag{3}$$

The CT protocol (OLA) will be more energy efficient than a non-CT protocol when $E_{\text{total, nc}} > E_{\text{total, c}}$. From (2) and (3), we get

$$E_{\text{rad}} \left(1 - \frac{1}{G_{\text{div}}(N_o)}\right) - (N_c - 1)(E_{\text{tx}} + E_{\text{rx}}) + n_{\text{oh}} \rho E_{\text{rx}} > 0.$$

By observing that $G_{\text{div}}(N_o)$ is a large number (on the order of 15 dB or 31 for as low as 2 orthogonal channels [14]), the above inequality becomes

$$E_{\text{rad}} - (N_c - 1)(E_{\text{tx}} + E_{\text{rx}}) + n_{\text{oh}} \rho E_{\text{rx}} > 0. \tag{4}$$

Interestingly, the high diversity gain plays no role in the energy comparison.

Since it is assumed that $N_c$ relay nodes are densely distributed (from Section II), it is reasonable to assume that the number of passive nodes that overhear during the second hop is also $N_c - 1$, resulting in $n_{\text{oh}} = 2(N_c - 1)$. Thus, (4) can be expressed as the following condition:

$$E_{\text{rad}} - (N_c - 1)\Big[E_{\text{tx}} + (1 - 2\rho)E_{\text{rx}}\Big] > 0. \tag{5}$$

The quantity on the left hand side of (5) is the energy difference between CT and non-CT. Expression (5) helps in gaining insight into the roles of the various parameters. A high value of $E_{\text{rad}}$ combined with low values of circuit energy consumption, i.e. of $E_{\text{tx}}$ and $E_{\text{rx}}$, will tend to favor CT. This is consistent with the conclusions of [8], [9], [10] that CT is favored in long-distance applications.

To quantify the energy-savings of CT relative to non-CT, we compute the 'Energy Ratio', $\mathcal{F}$, defined as the ratio of the total energy consumed by the non-CT protocol to the total energy consumed by the CT protocol. That is,

$$\begin{aligned}\mathcal{F} &= \frac{E_{\text{total, nc}}}{E_{\text{total, c}}} \\ &= \frac{E_{\text{tx}} + E_{\text{rad}} + (1 + 2(N_c - 1)\rho)E_{\text{rx}}}{N_c(E_{\text{rx}} + E_{\text{tx}})}.\end{aligned} \tag{6}$$

Note that $\mathcal{F} > 1$ implies that CT is more energy-efficient than non-CT.

## IV. Formulation in Terms of Radio Specific Parameters

Real sensor nodes have a maximum power output, and consequently a maximum range. From [8]-[10], it is clear that CT cannot be energy-efficient when the distance between communicating nodes is small. Therefore, we wish to compare CT with non-CT when the radios are operating at their highest power.

In order to evaluate (6), we need a model of the energy consumed by a relay node, in a form that distinguishes the radiated energy from the rest of the energy consumed by the node. Following [15], we consider the first-order model for $P_{\text{tx}}$, expressed as an affine function of the radiated power, $P_{\text{rad}}$:

$$P_{\text{tx}} = \alpha_{\text{tx}} + \beta_{\text{tx}} P_{\text{rad}},$$

where $\alpha_{\text{tx}}$ is the linearization constant, and $1/\beta_{\text{tx}}$ is defined as the marginal efficiency of the transmitter. So for a packet duration $T$, $E_{\text{tx}} = \alpha_{\text{tx}} T$ and $E_{\text{rad}} = \beta_{\text{tx}} P_{\text{rad}} T$. In the case of the radio operating at the highest power, $E_{\text{rad}} = \beta_{\text{tx}} P_{\text{rad}}^{\text{max}} T$, where $P_{\text{rad}}^{\text{max}}$ is the maximum radiated power. We also denote $P_{\text{rad}}^{\text{min}}$ as the minimum radiated power.

Because the supply voltage, $V$, is approximately constant, the energy consumption of a radio in a certain mode of operation is usually specified in terms of the supply current. Let $I_{\text{tx}}^{\text{min}}$ be the current when the radio is transmitting at its lowest radiated power, and let $I_{\text{tx}}^{\text{max}}$ be the current for the maximum radiated power. Let $I_{\text{rx}}$ be the current when the radio is receiving data. We observe that

$$\begin{aligned} I_{\text{tx}}^{\text{max}} \cdot V &= \alpha_{\text{tx}} + \beta_{\text{tx}} P_{\text{rad}}^{\text{max}}, \\ I_{\text{tx}}^{\text{min}} \cdot V &= \alpha_{\text{tx}} + \beta_{\text{tx}} P_{\text{rad}}^{\text{min}}. \end{aligned} \tag{7}$$

By solving (7) for $\alpha_{\text{tx}}$ and $\beta_{\text{tx}}$, we get

$$\begin{aligned} \alpha_{\text{tx}} &= \left( \frac{P_{\text{rad}}^{\text{max}} I_{\text{tx}}^{\text{min}} - P_{\text{rad}}^{\text{min}} I_{\text{tx}}^{\text{max}}}{P_{\text{rad}}^{\text{max}} - P_{\text{rad}}^{\text{min}}} \right) \cdot V, \text{ and} \\ \beta_{\text{tx}} &= \left( \frac{I_{\text{tx}}^{\text{max}} - I_{\text{tx}}^{\text{min}}}{P_{\text{rad}}^{\text{max}} - P_{\text{rad}}^{\text{min}}} \right) \cdot V. \end{aligned}$$

Substituting $E_{\text{tx}} = \alpha_{\text{tx}} T$, $E_{\text{rad}} = \beta_{\text{tx}} P_{\text{rad}}^{\text{max}} T$, and $E_{\text{rx}} = I_{\text{rx}} V \cdot T$ into (6), we get

$$\mathcal{F} = \frac{\alpha + \beta P_{\text{rad}}^{\text{max}} + (1 + 2(N_c - 1)\rho) I_{\text{rx}}}{N_c(I_{\text{rx}} + \alpha)}, \tag{8}$$

where $\alpha = \alpha_{\text{tx}}/V$ and $\beta = \beta_{\text{tx}}/V$. Since $I_{\text{tx}}^{\text{max}}$, $I_{\text{tx}}^{\text{min}}$, $I_{\text{rx}}$, $P_{\text{rad}}^{\text{max}}$ and $P_{\text{rad}}^{\text{min}}$ are radio specific parameters, $\mathcal{F}$ is function of $N_c$ and $\rho$ when the radio device is fixed.

TABLE I
Currents and powers for different radios

| Parameter | CC1021 | CC2420 | XE1205 | nRF2401 | nRF905 |
|---|---|---|---|---|---|
| $I_{\text{tx}}^{\text{max}}$ | 25.1 mA | 17.4 mA | 62 mA | 13 mA | 30 mA |
| $I_{\text{tx}}^{\text{min}}$ | 14.5 mA | 8.5 mA | 25 mA | 8.8 mA | 9 mA |
| $I_{\text{rx}}$ | 19.9 mA | 19.7 mA | 14 mA | 19 mA | 12.5 mA |
| $P_{\text{rad}}^{\text{max}}$ | 5 dBm | 0 dBm | 15 dBm | 0 dBm | 10 dBm |
| $P_{\text{rad}}^{\text{min}}$ | -20 dBm | -25 dBm | 0 dBm | -20 dBm | -10 dBm |

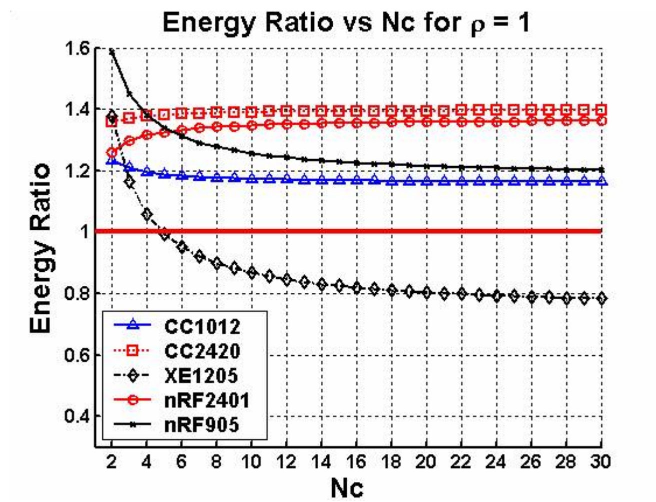


Fig. 2. Energy Ratio, $\mathcal{F}$ for the different sensors as a function of the number of cooperators, $N_c$ for full decode ($\rho = 1$) .

## V. Results

In this section, we consider the energy and power profiles of a few radios that are available today and evaluate whether or not CT offers energy-savings relative to non-CT for these profiles. Table I gives the permissible currents and powers for three currently available radios, CC1021 [16], CC2420 [11], XE1205 [17], and the Nordic devices, nRF2401 [18] and nRF905 [19]. We acknowledge that none of these radios support OLA transmission because they do not provide diversity reception. However, we still consider them because we think their characteristics would be similar to OLA-supporting radios, and also because they show how the differences between radios affect the results.

Fig. 2 is a plot of the energy ratio, $\mathcal{F}$, versus the number of cooperators, $N_c$, for $\rho = 1$. We remark that $\rho = 1$ means that the relay nodes must decode the whole packet to decide whether they should be involved in relaying the packet or not. As can be seen from Fig. 2, CT uses less energy than non-CT for all $N_c$'s when $\rho = 1$ except for XE1205. This is contrary to what we expected which was that CT would be most beneficial for the highest powered radio. The reason why XE1205 loses its benefit as $N_c$ increases is because it requires relatively high circuit energy for transmission ($E_{\text{tx}}$).

With a simple derivation, we can find that $\mathcal{F}$ converges to $2\rho E_{\text{rx}}/(E_{\text{tx}} + E_{\text{rx}})$ as $N_c$ increases. This saturating point is 1.1581 for CC1012 and 0.7409 for XE1205 when $\rho = 1$. Therefore, for all radios except XE1205 and $\rho = 1$, $\mathcal{F}$ is

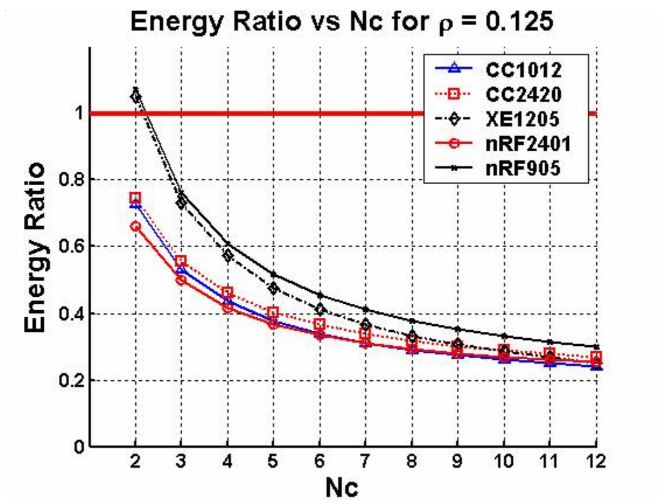


Fig. 3. Energy Ratio, $\mathcal{F}$, for the different sensors as a function of the number of cooperators, $N_c$ for partial decode ($\rho = 0.125$) .

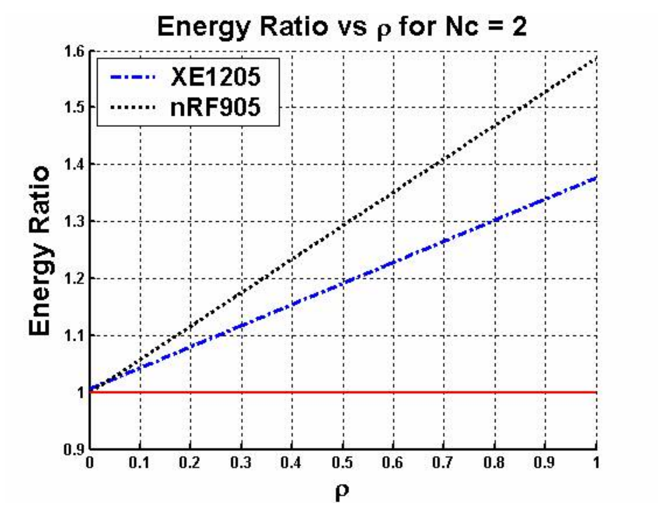


Fig. 4. Energy Ratio, $\mathcal{F}$, for XE1205 and nRF905 as a function of $\rho$ when $N_c = 2$.

greater than 1.15 regardless of $N_c$, which indicates that CT extends the network life relative to non-CT by at least 15% when passive nodes decode the whole packet.

Fig. 3 shows the case of $\rho = 0.125$. The reason why we pick this value is that according to the ZigBee Standard [20], preamble and headers (PHY and MAC) are 16 bytes and the largest data packet is 128 bytes. If we assume each node *must* decode the MAC header in order to make a decision on participating in the relay and longest available data packet is used, then $\rho = 0.125$. As can be seen from Fig. 3, CT does not save energy when $N_c \geq 3$. However, with $N_c = 2$, XE1205 and nRF905 can save energy. Therefore, if the sensor nodes are intelligent enough to do partial decoding for decision making and its data packet length is large relative to the header, CT never saves energy for $N_c$ larger than 2.

As already discussed above (Fig. 3), the XE1205 and nRF905 profiles correspond to energy savings using CT when

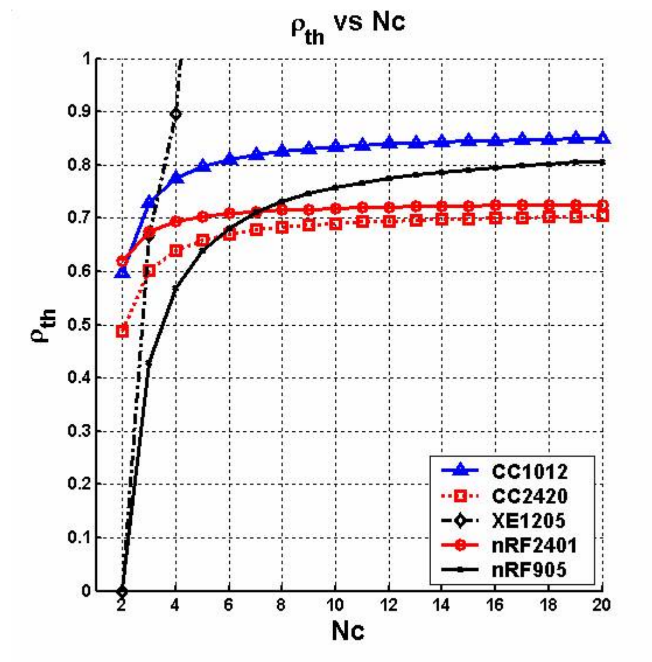


Fig. 5. Threshold for $\rho$ ($\rho_{th}$) above which the CT saves the energy.

$N_c = 2$ and when the payload is the maximum size. To examine the energy ratio for smaller payloads, we plotted Fig. 4, which shows $\mathcal{F}$ versus $\rho$ for XE1205 and nRF905 when $N_c = 2$, still assuming the same header and maximum packet lengths. As can be seen from the graph, CT is more energy-efficient than non-CT for all values of $\rho$. For example, when the total packet length is 80 Bytes or less ($\rho \geq 0.2$), XE1205 and nRF905 using CT can save at least 7.4% and 10%, respectively, of the energy compared to non-CT.

Since all the energy profiles except one yield an energy ratio greater than one for $\rho = 1$, we were curious to find the minimum value of $\rho$, denoted $\rho_{th}$, for which CT would save energy relative to non-CT. These threshold values are plotted in Fig. 5 versus $N_c$ for each radio energy profile. For XE1205, there is no $\rho_{th}$ for $N_c \geq 5$, which is readily predicted by Fig. 2. Therefore, for XE1205, regardless of the ability of partial decoding and length of the data packet, CT consumes more energy than non-CT when the cooperating nodes are more than 4. For other radios except for XE1205, CT will use less energy if radios cannot do partial decoding or length of the data packet is very small. For example, for nRF905 with $N_c = 16$, length of the data packet should be less than 20 bytes in order for CT to be energy-efficient. As another example, for $N_c = 2$, and CC2420, CT would be advantageous for payloads of 32 bytes or less.

## VI. Conclusion

This paper has compared the energy benefit of cooperative transmission (CT) to a non-CT approach for a single-cluster, two-hop network for a fixed constellation size. It was shown that the energy consumed by passive nodes, or nodes that decode at least a part of a packet without relaying, can be significant and can affect the CT and non-CT comparison when power and energy profiles consistent with today's radios are assumed. When passive nodes decode the whole packet, CT was shown to be beneficial for most profiles considered regardless of the payload size. However, when passive nodes decode only the header, CT was shown to not always be beneficial, and its performance was found to depend on the number of cooperators and the payload size. If CT is used for XE1205 or nRF905 when there are only two cooperating nodes, energy-saving can be achieved for all payload sizes up to the maximum specified by the ZigBee standard.

## VII. Acknowledgement

The authors gratefully acknowledge support for this research from the National Science Foundation under grant CNS-0721296.

## References

[1] M. J. Sailor and J. R. Link, "Smart dust: nanostructured devices in a grain of sand."

[2] A. Scaglione and Y. W. Hong, "Opportunistic large arrays: Cooperative transmission in wireless multihop ad hoc networks to reach far distances," vol. 51, no. 8, pp. 2082–2092, Aug. 2003.

[3] Y. Yao, X. Cai, and G. B. Giannakis, "On energy efficiency and optimum resource allocation of relay transmissions in the low-power regime," *IEEE Trans. Wireless Commun.*, vol. 4, no. 6, pp. 2917–2927, Nov. 2005.

[4] M. Dohler, A. Gkelias, and A. H. Aghvami, "Capacity of distributed phy-layer sensor networks," *IEEE Trans. Veh. Technol.*, vol. 55, no. 2, p. 622, Mar. 2006.

[5] I. Maric and R. D. Yates, "Cooperative multicast for maximum network lifetime," *IEEE J. Select. Areas Commun.*, vol. 23, no. 1, pp. 127–135, Jan. 2005.

[6] F. H. Fitzek and M. D. Katz, *Cooperation in Wireless Networks: Applications and Principles*, 1st ed. Berlin, Germany: Springer-Verlag, 2006.

[7] A. Kailas, L. V. Thanayankizil, and M. A. Ingram, "A simple cooperative transmission protocol for energy-efficient broadcasting over multi-hop wireless networks," *KICS/IEEE Journal of Communications and Networks (Special Issue on Wireless Cooperative Transmission and Its Applications)*, vol. 10, no. 2, p. 213, June 2008.

[8] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of mimo and cooperative mimo techniques in sensor networks," *IEEE Trans. Wireless Commun.*, vol. 22, no. 6, pp. 1089–1098, Aug. 2004.

[9] L. Simic, S. M. Berber, and K. W. Sowerby, "Energy-efciency of cooperative diversity techniques in wireless sensor networks," in *IEEE PIMRC*, Oct. 2007.

[10] S. K. Jayaweera, "Virtual mimo-based cooperative communication for energy-constrained wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 5, no. 5, p. 984, May 2006.

[11] "CC2420." Chipcon. [Online]. Available: http://focus.ti.com/lit/ds/symlink/cc2420.pdf

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

[13] G. L. Stuber, *Principles of Mobile Communication*, 2nd ed. Kluwer Academic Publishers, 2002.

[14] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[15] J. Ammer and J. Rabaey, "The energy-per-useful-bit metric for evaluating and optimizing sensor network physical layers," in *IEEE SECON*, vol. 2, Sept. 2006, pp. 695–700.

[16] "CC1021." Chipcon. [Online]. Available: http://focus.ti.com/lit/ds/symlink/cc1021.pdf

[17] "XE1205." XEMICS. [Online]. Available: http://www.btnode.ethz.ch/pub/uploads/Projects/

[18] "nRF2401." Nordic Semiconductor. [Online]. Available: http://www.nordicsemi.com/index.cfm?obj=product&act=display&pro=64

[19] "nRF905." Nordic Semiconductor. [Online]. Available: http://www.nordicsemi.com/index.cfm?obj=product&act=display&pro=83

[20] "Zigbee alliance, ieee 802.15.4, zigbee standard." ZigBee Alliance. [Online]. Available: http://www.zigbee.org