Minimizing Energy Consumption for Cooperative Network and Diversity Coded Sensor Networks

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Gabriel E. Arrobo and Richard D. Gitlin

Department of Electrical Engineering

University of South Florida, Tampa, Florida, USA

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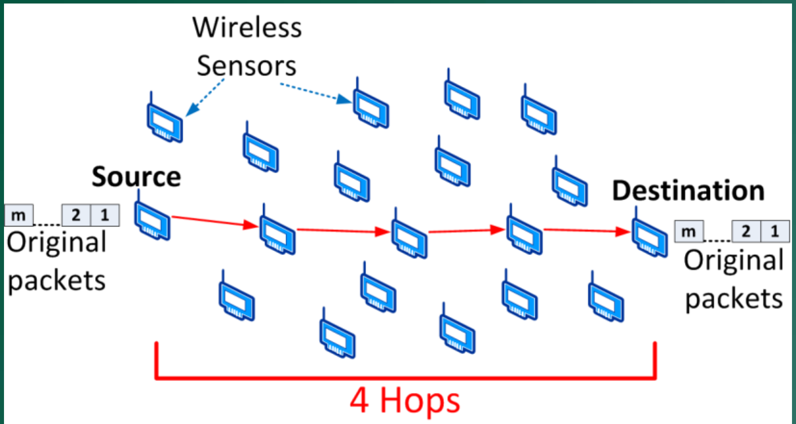
Objective

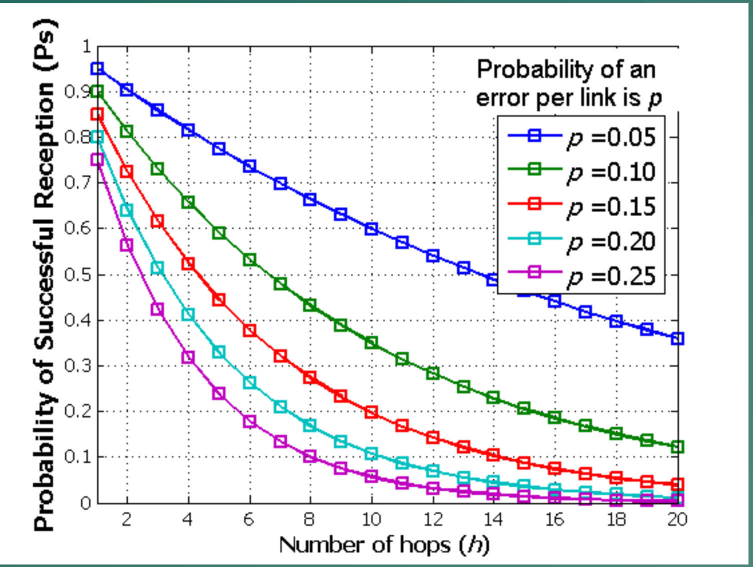
- The aim of this paper is to explore novel approaches for improving throughput and reliability of wireless sensor networks while minimizing the energy consumption.

Classic Wireless Sensor Networks

- In wireless sensor networks, a path (a sequence of nodes between the source and the destination) is chosen and then packets are forwarded, or routed, along the path.
- To overcome link-level packet loss and to avoid significant end-to-end throughput degradation, networks often use link-level retransmissions.
- Moreover, if any packet is “lost” during the transmission, that specific packet is retransmitted from the source node.
  - However, there is no guarantee that the retransmitted packet can be correctly received by the destination node.



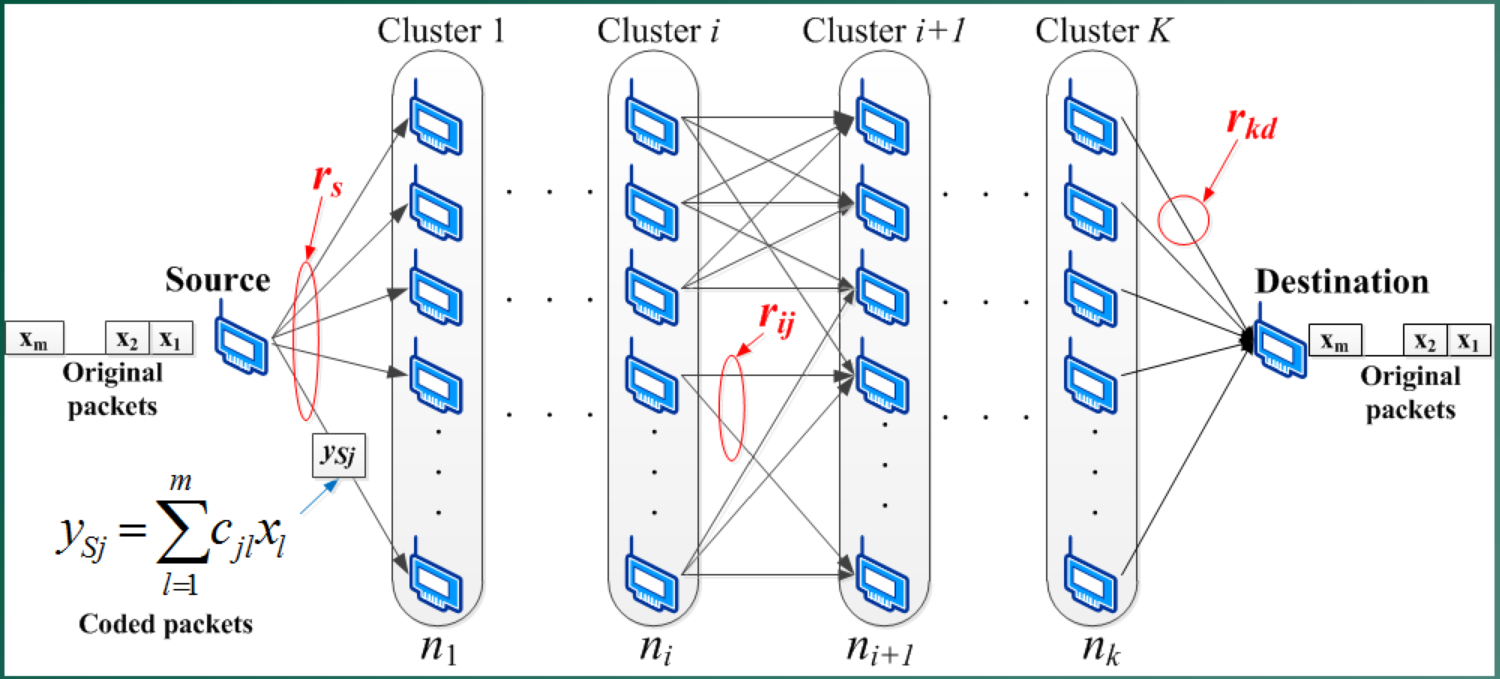
Wireless Sensor Network



Wireless Sensor Network - Hops

Cooperative Network Coding

- Cooperative Network Coding (CNC) synergistically integrates Network Coding with cluster-based Cooperative Communications to improve network reliability and enhance network performance.
- CNC is a technology that exploits the massive deployment of nodes in wireless sensor and other networks
- CNC is based on Dr. Haas' work [1] and is enhanced by our analysis and evaluation of the effects of retransmissions.



Cooperative Network Coding

CNC – Parameters

- The table below shows the system parameters for Cooperative Network Coding.

Parameter	Description
n_i	Number of nodes in the cluster i
K	Number of clusters between the source and the destination
r_s	Number of nodes in the cluster 1 that are connected to the source node
r_{ij}	Number of nodes in the cluster i+1 that are connected with node (i, j)
r_{Kd}	Whether node (K, j) is connected to the destination node or not
$p_{(i,j)(i+1,l)}$	Probability of link error between node (i, j) and node (i+1, l)
m	Number of original packets in a block (i.e., block size)
m'	Number of coded packets transmitted by the source node

Note that the probability of link error between node (i, j) and node (i+1, j) depends on the transmission power, channel conditions, modulation scheme, and packet length, among other factors.

CNC – Operation

- The source create coded packets y_j from the original (uncoded) packets x_k and transmits coded packets towards the nodes in cluster 1.
- A cluster is (dynamically) formed by a group of nodes geographically located close to each other.
  - The coded packets are calculated as:

$$y_j = \sum_{k=1}^{m} c_{jk} x_k \qquad j = \{1, 2, 3, \dots, m'\}$$

  - The addition and multiplication operations are performed over a $GF(2^q)$
- Nodes in cluster 1 create a coded packet from the received packets and transmit it towards the next cluster.
- Nodes, in cluster 2 through K, receive the coded packets, create a coded packet and transmit it to the next cluster.
- The destination receives coded packets from cluster K and decodes the original message.
- The sink must receive at least m linearly independent packets necessary to recover the original information.

Minimizing Energy Consumption: CNC

- The energy required to network code a packet is calculated as:

$$E_{NC} = mE_{LFSR} + \frac{L}{q}(mE_{MUL} + (m-1)E_{ADD})$$

  Where:
  - E_{LFSR} is the energy required to generate the random coefficients using linear feedback shift register (LFSR),
  - L is the packet length in bits,
  - q is the field size, $GF(2^q)$,
  - E_{MUL} is the energy require to multiply a random coefficient and the packet (portion of the packet that depends on the Galois Field size), and
  - E_{ADD} is the energy required to add the results of two multiplication processes.
- Since with Network Coding, all the packets are coded, the energy required for each node to code m' packets is:

$$E_{NODE_{NC}} = m'\left(mE_{LFSR} + \frac{L}{q}(mE_{MUL} + (m-1)E_{ADD})\right)$$

CNC – Energy (contd.)

- In Network Coding, the linear independency of the coded packets is a function of the field size.
  - Thus, the expected number of transmitted packets until transmitting m linearly independent coded packets, when using *RLNC*, can be calculated as:

$$M' = \sum_{l=1}^{m} \frac{1}{1 - \left(\frac{1}{2^q}\right)^i}$$

- The average probability p_l of the m' coded packets being linearly independent:

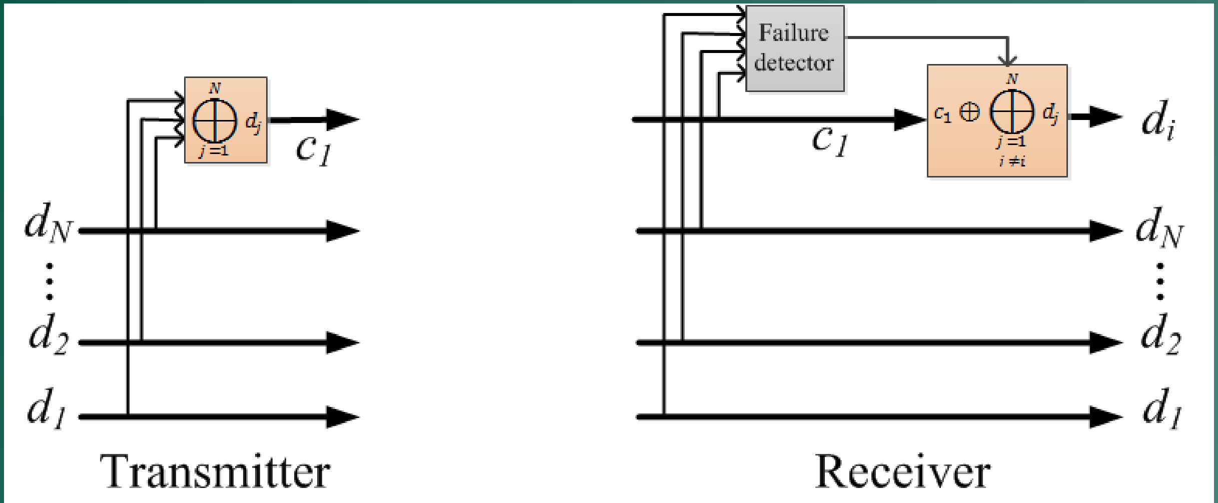
$$p_l = \frac{m}{m'}$$

- As we can see with *RLNC*, the source node needs to transmit a number of coded packets m' that is at least the smallest integer not less than *M*'.

$$m' = \lceil M' \rceil = \left\lceil \sum_{l=1}^{m} \frac{1}{1 - \left(\frac{1}{2^q}\right)^i} \right\rceil$$

Cooperative Diversity Coding – Overview

- Diversity Coding (DC) [12] is an established feed-forward spatial diversity technology that enables near instant self-healing and fault-tolerance in the presence of link failures.
- The protection information (c_i) carries a combination of the data lines (d_j).
- The figure below shows a Diversity Coding system that uses a spatial parity check code for a point-to-point system with N data lines and 1 protection line.
  - If any of the data lines fail (e.g. d_3), through the protection line (c_1), the destination (receiver) can recover the information of the data line that was lost (d_3).



Diversity Coding system $(1 - for - N)$

Diversity Coding (DC) – Details

- Diversity Coding improves network reliability →Information is transmitted through spatially different paths.

- The coding coefficients $\left(\beta_{ij}\right)$ are calculated as:

$$\beta_{ij} = \alpha^{(i-1)(j-1)} \qquad i = 1, 2, \dots, N;\ j = 1, 2, \dots, M$$

where α is a primitive element of $GF(2^q)$ and $q \geq \lceil \log_2(M + N + 1) \rceil$.

  – Since the coding coefficients are known by the source and destination nodes, there is no need to transmit the β_{ij} coefficients in the packet header.

$$\beta = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 & \cdots & \alpha^{N-1} \\ 1 & \alpha^2 & \alpha^4 & \cdots & \alpha^{2(N-1)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \alpha^{M-1} & \alpha^{(M-1)2} & \cdots & \alpha^{(M-1)(N-1)} \end{bmatrix}$$

- Since the coding coefficients are known by the source and destination nodes, there is no need to transmit the coefficients in the packet header.

CDC – Energy

- The energy required to diversity code a packet is calculated as:

$$E_{DC} = \frac{L}{q}(mE_{MUL} + (m-1)E_{ADD})$$

  Where:
  - L is the packet length in bits,
  - q is the field size, $GF(2^q)$,
  - E_{MUL} is the energy require to multiply a random coefficient and the packet (portion of the packet that depends on the Galois Field size), and
  - E_{ADD} is the energy required to add the results of two multiplication processes.
- Since with Network Coding, all the packets are coded, the energy required for each node to code m' packets is:

$$E_{NODE_{DC}} = (m'-m)E_{DC}$$

$$E_{NODE_{NC}} = (m'-m)\frac{L}{q}(mE_{MUL} + (m-1)E_{ADD})$$

Energy Savings : CDC

- As we can see from the previous equations, the source node requires less energy when using DC to create coded packets $\left(E_{SOURCE_{DC}}\right)$.
  - That is:

$$E_{SOURCE_{DC}} = E_{SOURCE_{NC}} - m'mE_{LFSR} - m\frac{L}{q}\left(mE_{MUL} + (m-1)E_{ADD}\right)$$

  - the second term on the right hand side of the equation is the energy savings for using known coding coefficients, and
  - the third term on the right hand side of the equation is the energy savings achieved for coding only the protection packets.
- The total number of transmitted packets in the network with CDC or CNC is the same and is calculated as:

$$E_{TOTAL} = m' + \prod_{i=1}^{K} n_i$$

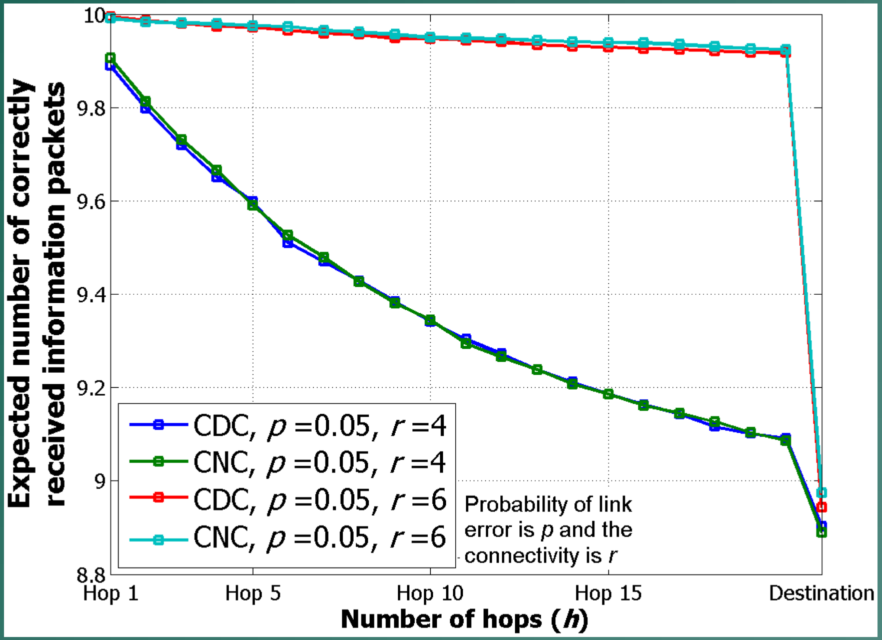
  - where K is the number of clusters between the source and destination nodes.
- However, as shown in above, the source requires less energy to code the packets with CDC compared to CNC.

Simulation Parameters

- The results presented in the following figures and tables were obtained through simulations by running 1,000 experiments.
  - An experiment is considered successful when the sink was able to decode the information from the source.
  - The coding operations were performed over a $GF(2^8)$.
- The parameters for the analyses and simulations of Cooperative Network Coding and Cooperative Diversity Coding are similar to the parameters used in [1]:
  - The number of original packets m is 10,
  - All the clusters have the same number of nodes $n = n_i$,
  - The network consists of 20 clusters $(K = 20)$,
  - The connectivity between node (i, j) and nodes in the cluster $i + 1$ is the same, $r = r_s = r_{ij}$ and,
  - All the links have the same characteristics, i.e., $p = p_{(i,j)(i+1,l)}$,
    - This assumption may be unrealistic but it simplifies the study.
    - Note that the probability of link error depends on the transmission power, channel conditions, modulation scheme, packet length, among other factors.

Results

- The figure below shows the performance of CDC and CNC given that the number of information packets is equal to the number of transmitted packets $(m = m')$
- As shown below, the source needs to transmit at least $m + 1$ combination packets otherwise the source needs to make a retransmission with very high probability.
- This is because the links between the source and the nodes in the first cluster are error prone.
- In other words, when the number of combination packets is equal to the number of information packets, regardless of the connectivity among the nodes and the probability of link error $\left(p_{s(1,j)} \neq 0\right)$, it is not possible to have full rank (at least m linearly independent packets) with high probability in the first cluster.



Results (contd.)

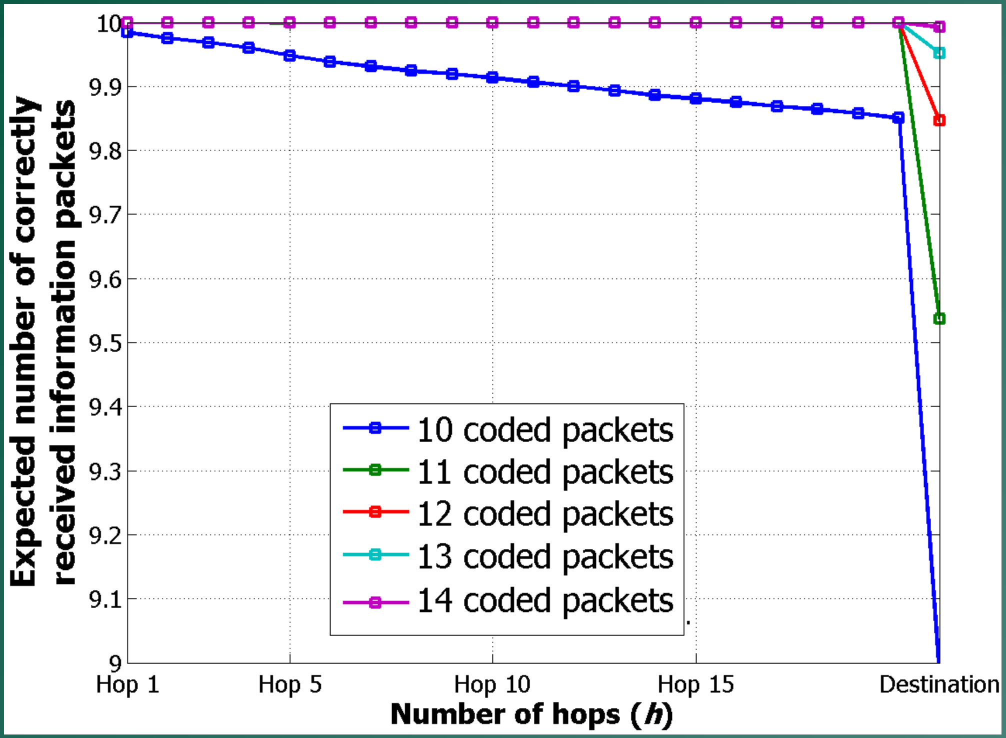
- The tables below show the linear independency of the packets at each cluster for CDC for a probability of link error of 0.10, given that the source node transmitted 11 coded packets.
  - On average, no need for a retransmission from the source node because cluster 11 has full rank and the retransmission can be made from those clusters.

Descriptive Statistics

		hop 1	hop 2	hop 3	…	hop 9	hop 10	hop 11	hop 12	…	hop 19	hop 20	Destination
N	Statistic	1000	1000	1000	…	1000	1000	1000	1000	…	1000	1000	1000
Range	Statistic	0	0	0	…	0	0	0	1	…	1	1	3
Minimum	Statistic	10	10	10	…	10	10	10	9	…	9	9	7
Maximum	Statistic	10	10	10	…	10	10	10	10	…	10	10	10
Mean	Statistic	10.00	10.00	10.00	…	10.00	10.00	10.00	10.00	…	10.00	10.00	9.60
	Std. Error	.000	.000	.000	…	.000	.000	.000	.001	…	.001	.001	.022
Std. Deviation	Statistic	.000	.000	.000	…	.000	.000	.000	.032	…	.032	.032	.696
Variance	Statistic	.000	.000	.000	…	.000	.000	.000	.001	…	.001	.001	.485
Skewness	Statistic	.	.	.	…	.	.	.	-31.623	…	-31.623	-31.623	-1.730
	Std. Error	.	.	.	…	.	.	.	.077	…	.077	.077	.077

Results (contd.)

- The figure below, along with the tables shown in the next chart, shows the most general case where full rank is achieved at a sufficient number of nodes including the last cluster, and a selective retransmission has to be made by the nodes in the last cluster for the destination to be able to decode the source's information.
- The expected number of information packets decoded at the destination as a function of the number of coded packets.
- Note that the source node should transmit at least $m + 1$ coded packets.



Results (contd.)

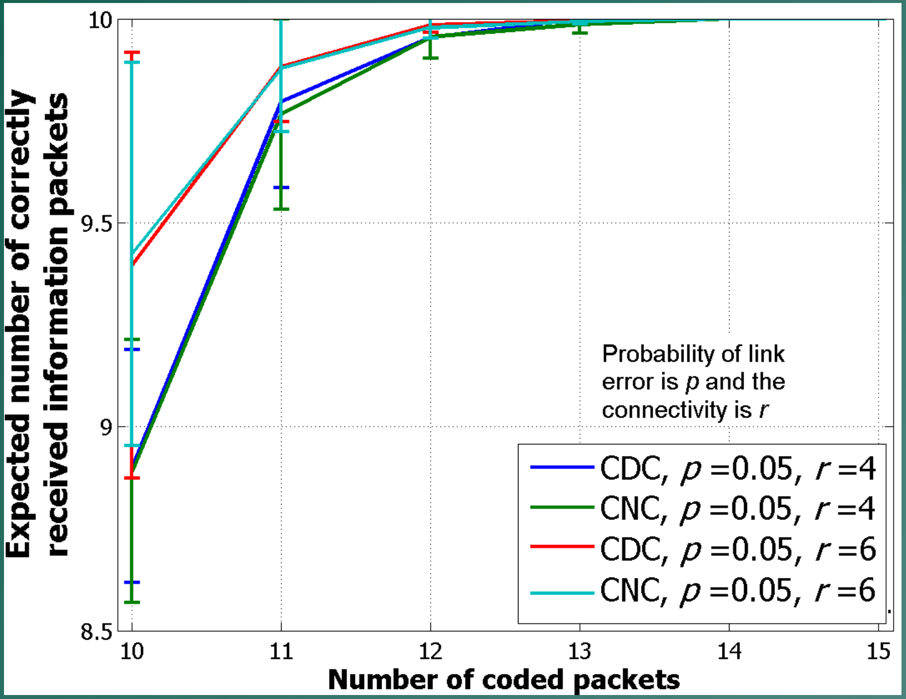
- The first table presents the results for CDC
  - Given that $p = 0.05$, $r = 6$ and $m' = 11$.
  - In the worst case 2 nodes in the last cluster need to retransmit a coded packet.

Descriptive Statistics

		hop 1	hop 2	hop 3	…	hop 14	hop 15	hop 16	hop 17	hop 18	hop 19	hop 20	Destination
N	Statistic	1000	1000	1000	…	1000	1000	1000	1000	1000	1000	1000	1000
Range	Statistic	0	0	0	…	0	0	0	0	0	0	0	2
Minimum	Statistic	10	10	10	…	10	10	10	10	10	10	10	8
Maximum	Statistic	10	10	10	…	10	10	10	10	10	10	10	10
Mean	Statistic	10.00	10.00	10.00	…	10.00	10.00	10.00	10.00	10.00	10.00	10.00	9.88
	Std. Error	.000	.000	.000	…	.000	.000	.000	.000	.000	.000	.000	.012
Std. Deviation	Statistic	.000	.000	.000	…	.000	.000	.000	.000	.000	.000	.000	.368
Variance	Statistic	.000	.000	.000	…	.000	.000	.000	.000	.000	.000	.000	.135
Skewness	Statistic	.	.	.	…	.	.	.	.	.	.	.	-3.298
	Std. Error	.	.	.	…	.	.	.	.	.	.	.	.077

CNC & CDC – Retransmissions

- The figure below shows the performance of CNC and CDC vs. the number of nodes per cluster.
- As it was expected, the performance of these two approaches increases when the number of nodes per cluster increases because there are more nodes in each cluster transmitting combination packets.
- However, increasing the number of nodes per cluster is not a preferred option because of the extra energy that is spent by the entire network.
- A better option is to retransmit from the last cluster, where the system still has full rank (linear independency of the combination packets).



Conclusions

- In this paper, we present an approach to minimize the energy consumption of multihop wireless packet networks, while achieving the required level of reliability.
- Our approach is to optimize and balance the use of forward error control, error detection, and retransmissions at the packet level for these networks.
- Additionally, we introduce Cooperative Diversity Coding (CDC), which is a novel means to code the information packets, with the aim of minimizing the energy consumed for coding operations.
- The performance of CDC is similar to CNC in terms of the probability of successful reception at the destination and expected number of correctly received information packets at the destination.

Conclusions (contd.)

- Selective retransmissions minimize both the energy consumed by the network and the delay, while achieving the desired throughput.
- The source need only transmit about 10% - 30% coded packets and utilize retransmission by the nodes in the last cluster that has full rank (100% linear independency among the packets) to minimize energy utilization.
- Achieving minimal energy consumption, with the required level of reliability is critical for the optimum functioning of many wireless sensor and body area networks.
- For representative applications, the optimized CDC or CNC network achieves ≥25% energy savings compared to the baseline CNC scheme.

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