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Cross-layer Design for Cooperative Wireless Sensor Networks with Multiple Optimizations

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Abstract

In virtual MIMO technology, distributed single-antenna radio systems cooperate on information transmission and reception as a multiple-antenna MIMO radio system. In this paper, a cooperative transmission scheme, virtual MIMO network formation and reconfiguration algorithms, and a cooperative routing backbone are cross-layered designed for wireless sensor networks (WSNs) to jointly achieve required reliability, energy efficiency and delay reduction. The proposed cooperative transmission scheme minimizes the number of intra communications among cooperative nodes. It can save energy and reduces latency at transmission links even when the distance between cooperative nodes is large. In the proposed routing backbone, energy consumption and latency are optimized simultaneously along the route which leverages the MIMO advantages from local transmission links into the whole network. In order to apply the virtual MIMO technology to a general WSN, the number of the cooperative nodes and the length of transmission links are allowed to have heterogeneity. The proposed virtual MIMO radio network can be formed for any underlying WSN with low reconfiguration cost. The performance evaluation shows that the proposed design can fully realize the potential of the virtual MIMO technology and largely improve reliability, latency and energy consumption in a WSN.

Keywords: wireless sensor networks, MIMO radio systems, cooperative wireless communication, cross-layer design, reconfigurable routing

1 Introduction

A multi-hop network of wireless micro sensor devices has been used for many real time applications such as environment monitoring and vehicle tracking [1]. Since a wireless micro sensor device is usually equipped with computational-capability constrained processor, single-antenna radio and limited battery power, high network performance and low energy consumption have been very challenging issues in the design of wireless sensor networks (WSNs). Multiple Input Multiple Output (MIMO) radio transceivers employ multiple digital adaptive transmission and reception antennas which can provide extremely high spectral efficiencies by simultaneously transmitting multiple data streams in the same channel. Diversity gain and Multiplex gain induced by MIMO technology have been used in wireless network for improving data transmission quality, extending transmission range, saving energy, and raising data rate [2, 3, 5, 6, 9, 10, 12, 13]. However, using terminal devices equipped with multiple antennas is unrealistic in many cases when considering the size, power consumption and cost of the terminal devices in WSNs. In this paper, we consider virtual MIMO technology that enables distributed single-antenna nodes cooperating on information transmission and reception as a MIMO radio system. In the cooperative communication, the cooperative WSN nodes at transmission and reception sides can be thought as a virtual MIMO node, respectively, and the transmission link between two virtual MIMO nodes can be thought as a virtual MIMO link.

In [3], S. Cui and *et al* proposed a cooperative MIMO transmission scheme that transmits multiple source data between two virtual MIMO nodes. In the scheme, there are multiple single-antenna WSN nodes at transmission side and reception side cooperating on data transmission and reception. The scheme minimizes the energy consumption and transmission delay through variable data rate by adjusting the constellation size (bits per symbol). However, the scheme needs a large amount of intra transmissions at virtual MIMO nodes. The performance evaluation shows that the scheme uses less energy with lower latency than the traditional non-cooperative Single Input Single Output (SISO) transmission scheme when the diameter of virtual MIMO nodes is less than 2 meters, where the diameter is defined as the largest distance between cooperative WSN nodes inside a virtual MIMO node. In [6], a similar cooperative transmission scheme was proposed. In order to reduce the transmission energy, it assumes that multiple l-bit source data can be aggregated into one single l-bit data which may not be true in some applications. In [13], Y. Yuan and *et al* proposed a cooperative MISO (Multiple Input Single Output) transmission scheme, where multiple WSN nodes work on transmission cooperatively and one WSN node works on reception. Comparing to the schemes in [3, 6], the MISO scheme requires less intra transmissions at virtual MIMO nodes. In [5, 6, 13], routing protocols are jointly designed with the cooperative transmission scheme. In [6, 13], virtual MIMO nodes are formed (i.e., cooperative nodes are selected) at each transmission link along the route in every routing process, which brings a large computational overhead. In [5, 13], the diameter and size (the number of cooperative WSN nodes) of each virtual MIMO node and the length of each virtual MIMO link have to be the same. It is unrealistic to construct a virtual MIMO network under such conditions unless the underlying WSN is very dense or the sensor nodes are manually deployed. In the above research works, the performance is evaluated through the comparison only with the traditional non-operative approach.

In this paper, a cooperative Multi-MISO transmission scheme, virtual MIMO network formation and reconfiguration algorithms and a cooperative routing backbone are cross-layered designed for WSNs to jointly achieve required reliability, energy efficiency and delay reduction. The proposed transmission scheme minimizes intra transmissions among the cooperative nodes. It can save energy and reduce delay by achieving diversity gain and multiplex gain simultaneously at transmission links even when the diameters of virtual MIMO nodes more is large. Given a required error rate, energy and latency are simultaneously optimized along the route under multiple parameters of bandwidth, size and diameter of virtual MIMO nodes, and length of a virtual MIMO link by adjusting the constellation size. In order to apply virtual MIMO technology to a general WSN, the virtual MIMO nodes and links are allowed to have heterogeneity. That is, the number of WSN nodes in a virtual MIMO node, the diameter of a virtual MIMO node and the length of a virtual MIMO link can be different. In our design, the virtual MIMO radio network and cooperative routing backbone are formed and initialized only once. With low cost reconfiguration functions, they can stay in use during the whole network lifetime, which largely reduces the computation and communication overhead in the approaches that need to form virtual MIMO nodes and links in every routing process. In the performance evaluation, we compare our approach with both the traditional SISO non-cooperative approach and other virtual MIMO cooperative approaches. The result shows that the proposed design has the better performance than other approaches and it can fully realize the potential of the virtual MIMO technology and largely improve reliability, latency and energy consumption in a WSN.

The rest of the paper is organized as follows: In Section 2, the model of virtual MIMO radio network for an underlying WSN is introduced. In Section 3, a cooperative Multi-MISO transmission scheme is proposed. The energy and latency in the scheme is evaluated through numerical analysis and computer simulation. In Section 4, virtual MIMO network and routing backbone formation and reconfiguration algorithms, and routing protocols are proposed. The network performance is evaluated through computer simulations. Finally, Section 5 gives the conclusion.

2 Virtual MIMO Radio Network Model

Let a WSN be represented by a undirected graph $G = (V, E)$, where V is the set of wireless sensor nodes equipped with a single-antenna radio and E is the set of the edges of G. An edge e is defined as $e = (u, v) \in E$ if and only if $u, v \in V$ and u and v are in the communication range with each other. A *d-clustering* of V is a node disjoint division of V into a set of *d-clusters* such that the distance between any pair of nodes in a d-cluster is not larger than d. Let A and B be two d-clusters, and A' and B' be the subsets of A and B with mt nodes in A' and mr nodes in B', respectively. If the largest distance between any pair of a node in A' and a node in B' is not larger than D, a $D - mt \times mr$ virtual MIMO link can be defined between A and B, where the ith node in A' uses its antenna as the ith antenna cooperating the transmission and the jth node in B' uses its antenna as the jth antenna cooperating the reception as a MIMO transmission link. According to $mt = mr = 1$, $mt > 1$ and $mr = 1$, $mt = 1$ and $mr > 1$, $mt > 1$ and $mr > 1$, the virtual MIMO link is called *SISO link*, *MISO link*, *SIMO link* and *MIMO link*, respectively. Usually, d is much smaller than D. A virtual MIMO radio network of the WSN can be represented as undirected graph $G_{VMIMO} = (V_{VMIMO}, E_{VMIMO})$, where V_{VMIMO} is the set of the d-clusters, and E_{VMIMO} is the set of edges. An edge $(A', B') \in E_{VMIMO}$ if and only if there is a $D - mt \times mr$ virtual MIMO link defined between A' and B', where $A' \subset A, B' \subset B, A, B \in V_{VMIMO}$ and there are mt nodes in A' and mr nodes in B', respectively. According to the definition, multiple SISO, SIMO, MISO or MIMO links can be formed between two clusters A and B. We will discuss it in the following sections. In the virtual MIMO network, the size (the number of WSN nodes), and diameter of a cluster, and the length of virtual MIMO links can be different. In the rest of the paper, the clusters are also called virtual MIMO nodes, and the nodes of the WSN form the clusters are called *primary nodes*. In each virtual MIMO node there is a special primary node called *head node* and other primary nodes are called as *member nodes*. The head node is supposed to know its member nodes' information such as their IDs and battery power levels, and the member nodes know the head's information, too. If $(A', B') \in E_{VMIMO}$, A' is supposed to know B's information such as the size and diameter of B' and vice versa. In this paper, we focus on the problem of relaying multiple source data back to the sink in a WSN. The same approach can be applied to other network functions in WSNs.

3 Cooperative Communication Schemes

In this section, we describe our Multi-MISO transmission scheme, and then compare it with Cui's MIMO scheme[3] and Yuan's MISO scheme [13] through numerical analysis.

3.1 Proposed Multi-MISO Scheme

Consider a cooperative relay process that relays k ($k \geq 1$) multiple source data in a virtual MIMO node A back to the sink. Suppose that there are mt primary nodes and mr primary nodes at transmission side A and reception side B in the first hop, respectively, and there is a *head* node at each side. Between A and B, mr virtual MISO links can be defined, where the ith ($1 \leq i \leq mr$) virtual MISO link is defined by mt nodes in A and the ith node in B. For instance, in Fig.1, there are three virtual MISO links defined between A and B, where each link is formed by four nodes in A and one node in B. The proposed scheme uses multiple MISO links instead of one virtual MIMO link between A and B. In the following, we argue that it can reduce the intra transmission in B. In a virtual MIMO link, the nodes in B have to cooperate on the data reception. For doing this, the information received at each node in B must be collected and sent to one node, say the head, for decoding, which requires intra communication in B. However, in a virtual MISO link, only one single node in B works on reception. Therefore, the decoding can be done at that node without any extra communication in B. The scheme uses multiple virtual MISO links to maximize the MIMO advantage. The cooperative transmission at each hop in the relay is described as follows:

Transmission at First Hop: mt nodes in A and mr nodes in reception side B cooperatively transmit k source information $I_1, I_2, \ldots, I_k$ from A to B (Fig. 1(a))

Step 1 (Intra/Local transmission at A)
Each node in A with source information broadcasts the information to all the other local nodes in A using different timeslots. After this step, each node has a source information sequence $I = I_1 I_2 \ldots I_k$.
In Fig. 1(a), there are three source information at the A side. After Step 1, all four nodes in A received three packets of information.

Step 2 (Transmission between A and B by using mr virtual MISO links)
Each node i ($1 \leq i \leq mt$) in A acts as the ith antenna and encode the sequence I using the MISO code system (i.e., $mt \times 1$ MIMO code system). All mt nodes in A broadcast encoded sequence to the mr nodes in B simultaneously. Each node in B receives mt encoded sequences, and then decodes them back to I according to the MISO code system independently.

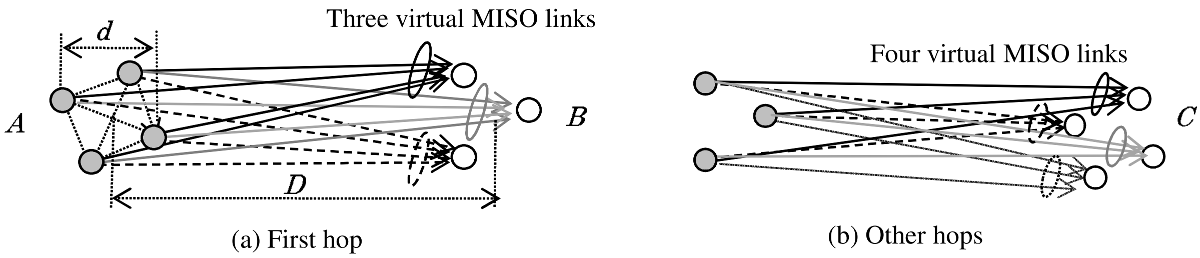


Figure 1: Cooperative Multi-MISO Scheme

Transmission at Other Hops: mt nodes in B at transmission side and mr cooperative nodes in C at reception side cooperatively relay source information sequence $I = I_1 I_2 \ldots I_k$ (Fig. 1(b))

Step 1 (Transmission between B and C by using mr virtual MISO links)
Each node i in B acts as the ith antenna and encode the sequence I using the MISO code system. All mt nodes in B broadcast the encoded sequence to the mr nodes in C simultaneously. Each node of mr nodes in C receives mt encoded sequences, and decodes them back to I.

From the second hop, there is no local transmission in both transmission and reception sides. Notice that for cluster-based cooperative network, the propagation delay between the nodes from transmitting cluster and receiver cluster would be different due to the discrepancy in geographical distance. However, the discrepancy in propagation delay is upper bounded because the cluster recruiting algorithm recruits nodes within certain geographical range. It has been proved that small synchronization error does not have much effect on the bit error rate (BER) performance of the system [7]. Simple and accurate synchronization algorithm [8] can also be implemented with very little energy consumption and latency.

3.2 Other Cooperative Communication Schemes

3.2.1 MIMO Scheme [3]

In the MIMO scheme, cooperative nodes in transmission side A and cooperative nodes in reception side B form a single MIMO link (Fig. 2). The information received at each node in B need to be collected and sent to the head node for decoding. Therefore, the scheme needs one more step than the Multi-MISO Scheme for local communication at B.

Transmission at First Hop (Fig. 2(a)):

Step 1 (Intra/Local transmission at *A*): This step is the same as Step 1 in the Multi-MISO Scheme.

Step 2 (Transmission between *A* and *B* with a $mt \times mr$ virtual MIMO link): Each node i in A acts as the ith antenna and encode the sequence $I = I_1 I_2 \ldots I_k$ using the MIMO code system. All mt nodes in A broadcast the encoded sequence to the mr nodes in B simultaneously.

Step 3 (Intra/Local transmission at *B*): Each node in B transmits the received sequences I using different time slots to the head node. The head node decodes the mr sequences it received back to I using the MIMO code system.

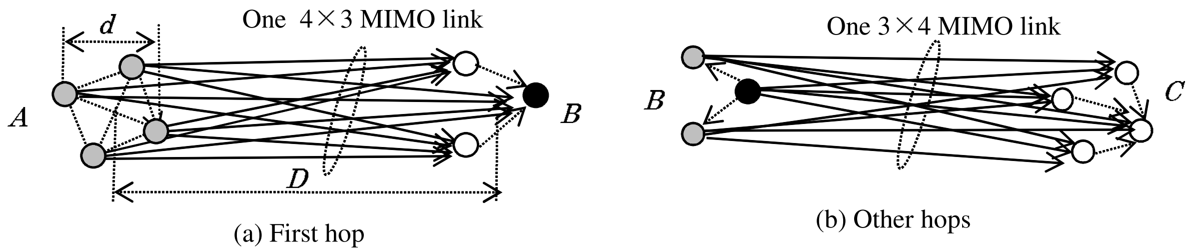


Figure 2: Cooperative MIMO Scheme

Transmission at Other Hops (Fig. 2(b)):

Step 1: The head node at the transmission side broadcasts the sequence I to other local nodes.

Step 2 and Step 3: They are the same as those in the first hop.

3.2.2 MISO-Scheme [13]

In the MISO Scheme, cooperative nodes in virtual node A and the head node in B form a single MISO link (Fig. 3).

Transmission at First Hop :

Step 1 (Intra/Local transmission at *A*): Each node with source information transmits its information to the head using different timeslots. The head broadcasts received sequence $I = I_1 I_2 \ldots I_k$ to the mt cooperative nodes (mt cooperative nodes and the source nodes can overlap with each other).

Step 2 (Transmission between A and B with a single MISO link): Each cooperative node i acts as the ith antenna and encode the sequence using the MISO code system. All mt nodes in A transmit the encoded sequence to the head node in B simultaneously. The head in B decodes the received mt sequences back to I using the MISO code system.

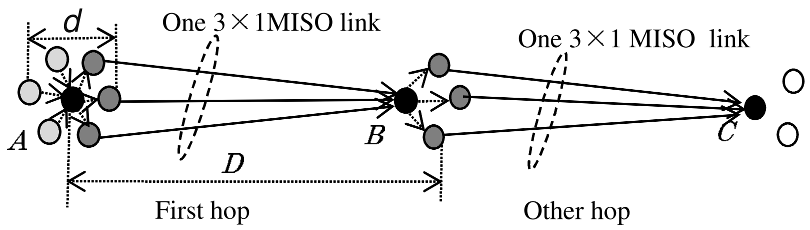


Figure 3: Cooperative MISO Scheme for transmitting multiple source data

Transmission at Other Hops :

Step 1 : The head node at the transmission side broadcasts the sequence I to other local nodes.

Step 2 : It is the same as Step 2 in the first hop.

Comparing to the proposed Multi-MISO Scheme, the MISO Scheme needs extra local communication in Step 1 from the second hop.

3.3 Energy and Latency Analysis

In this paper, the MIMO systems are referring to the ones coded with space-time block codes (such as Alamouti code) and a flat Rayleigh fading channel as those used in [3]. The path loss is modeled as a power fall off proportional to the distance squared. Given bandwidth B and constellation size b (bits per symbol), bB bits can be transmitted per second. We consider a variable-rate system, where b can be different at each virtual MIMO link. In order to keep the model from being over-complicated, signal processing blocks (source coding, pulse-shaping, digital modulation and channel coding) are intentionally omitted. The methodology used here can be extended to use other MIMO codes and include the signal processing blocks. We first give the equations of the energy consumption and latency for traditional SISO Scheme, Multi-MISO Scheme, MIMO Scheme, and MISO Scheme, and then optimize them under multiple parameters of bandwidth, diameter of virtual nodes, length of MIMO links by adjusting the constellation size.

3.3.1 Formulas

The following formulas are used for evaluating energy and latency and can be found in [3, 4]. For local transmission, a κ-th power path loss with AWGN is assumed. We use $e^L(r)$ to denote the energy cost per bit for broadcasting information from one node to r nodes at local virtual MIMO nodes. Since usually the long-haul distance D between two virtual MIMO nodes is much larger than the diameter d of the virtual nodes, we assume that the long-haul transmission distance is the same between each node of the transmission side and each node of the reception side in a virtual MIMO link. We use $e^{MIMO}(mt, mr)$ to denote the energy cost per bit for long-haul MIMO link with mt cooperative nodes in transmission side and mr cooperative nodes in reception side. We use $e^{MISO}(mt, r)$ to denote the energy cost per bit for long-haul r MISO links with mt cooperative nodes in transmission side and r nodes in reception side. In the formulas, P_b, B, d, D, b, n are the bit error rate (BER), bandwidth, diameter of virtual MIMO node, length of virtual MIMO link, constellation size, and information size at a source node, respectively, and P_{ct}, P_{cr}, P_{syn} are the circuit energy needed for transmission, reception and synchronization, $\bar{e}(P_b, b, mt, mr)$ is defined by the target BER, constellation size b, and number of cooperative nodes at transmission side and reception side. It can be calculated by numerical analysis according to the formulas in [4].

(1) $e^L(r) = (1+\alpha)\frac{4}{3}N_f\sigma^2\frac{(2^b-1)}{b}\ln\frac{4(1-2^{-\frac{b}{2}})}{bP_b}G_d + (P_{ct}+rP_{cr})\frac{1}{bB} + 2P_{syn}T_{tr}/n$

where $P_{ct} = 48.24, P_{cr} = 62.5, P_{syn} = 50\text{mw}, G_d = 10^7 \times d^\kappa, \kappa = 3.5, \alpha = \frac{3(\sqrt{2^b}-1)}{0.35(\sqrt{2^b}+1)}, N_f = 10\text{dB}, T_{tr} = 5\mu\text{s}$

(2) $e^{MIMO}(mt, mr) = (1+\alpha)\bar{e}(P_b, bmt, mr)\frac{(4\pi D)^2}{G_tG_r\lambda^2}M_lN_f + P_c(mt, r)$

where $P_c(t, r) = (tP_{ct} + rP_{cr} + 2P_{syn})/(bB), G_tG_r = 5\text{dBi}, M_l = 40\text{dB}$.

(3) $e^{MISO}(mt, r) = (1+\alpha)\bar{e}(P_b, b, mt, 1)\frac{(4\pi D)^2}{G_tG_r\lambda^2}M_lN_f + P_c(mt, r)$

3.3.2 Energy and Latency at the First Hop

In the evaluation, the symbol period is assumed to be $t_s = 1/B$. We suppose that in the first hop, there are mt nodes in transmission side A and mr nodes in reception side B, and k source information are cooperatively transmitted from A to B, where size of information bits is n_i at each source node i and total size of k source information is $n = \sum_{i=1}^{k} n_i$. Due to the multiplex gain induced by cooperative antennas, the constellation size can be raised to increase the data rate without changing the error rate. We use b^0, b^L, b^{MIMO}, and $b^{M\text{-}MISO}$ to denote the optimal constellation size in traditional transmission, intra transmission in virtual MIMO nodes, inter transmission at MIMO link, MISO link, and Multi-MISO links, respectively. In order to optimize the energy consumption and latency simultaneously, these constellation sizes are calculated by minimizing energy consumption in the corresponding energy terms. We use indices i and j to denote node i and node j at the cooperative transmission and reception sides, respectively.

(1) Traditional Non-Cooperative SISO Scheme

For the SISO long-haul transmission in the traditional non-cooperative approach, the energy per bit can be calculated as a special case of the MIMO system where $mt = mr = 1$. The energy and latency needed for transmitting k source in Traditional scheme can be found as follows:

$E_{tra} = \sum_{i=1}^{k} n_i e_i^{MIMO}(1,1)$ and $T_{tra} = t_s \sum_{i=1}^{k} \frac{n_i}{b_i^0}$

In order to minimize the energy consumption, the constellation size b_i^0 is selected by minimizing $e_i^{MIMO}(1,1)$ by using numerical techniques and formulas in Section 3.3.1.

(2) Cooperative MIMO Scheme

According to [5], in the MIMO Scheme, mr cooperative nodes at the receptions side quantize each symbol they receive into n_r bits, and then transmit all the bits to the head node. The energy and latency needed for transmitting k source information can be found as follows:

$$E_{MIMO} = \sum_{i=1}^{k} n_i e_i^L(mt-1) + e^{MIMO}(mt, mr)n + \sum_{j=1}^{mr-1} e_j^L(1)n_rn_s$$

$$T_{MIMO} = t_s(\sum_{i=1}^{k} \frac{n_i}{b_i^L(mt-1)} + \frac{n}{b^{MIMO}(mt, mr)} + \sum_{j=1}^{mr-1} \frac{n_rn_s}{b_j^L(1)})$$

In E_{MIMO} (T_{MIMO}), the first term is the energy (latency) needed for local transmission at A, where each node with source information transmits its information to other $mt-1$ nodes, the second term is the energy (latency) needed for transmitting information I of n bits from A to B using the virtual $mt \times mr$ MIMO link, and the third term is the energy (latency) needed for local transmission at B, where each node other than the head node in B transmits information I to the head node.

In order to minimize energy consumption, $b_i^L(mt-1)$, $b^{MIMO}(mt,mr)$, and $b_i^L(1)$ are selected by minimizing $e_i^L(mt-1)$, $e^{MIMO}(mt,mr)$ and $e_i^L(1)$, respectively, by using numerical techniques and formulas in Section 3.3.1. In E_{MIMO} and T_{MIMO}, $n_s = \frac{n}{b^{MIMO}}$.

(3) MISO Scheme

$$E_{MISO} = \sum_{i=1}^{k} n_i e_i^L(1) + e^L(mt-1)n + e^{MISO}(mt,1)n$$

$$T_{MISO} = t_s(\sum_{i=1}^{k} \frac{n_i}{b_i^L(1)} + \frac{n}{b^L(mt-1)} + \frac{n}{b^{MISO}(mt,1)})$$

In E_{MIMO} (T_{MIMO}), the first and second terms are the energy (latency) needed for local transmission at A, where the first term is the energy (latency) needed for each nodes with the source information transmits its information to the head, and the second term is the energy (latency) needed for transmitting information I of n bits to other $mt-1$ nodes. The third term is the energy (latency) needed for transmitting I from the A to B using the virtual $mt \times 1$ MISO link. The constellation size b in each term is selected in the same way described in (2).

(4) Proposed Multi-MISO scheme

$$E_{M\text{-}MISO} = \sum_{i=1}^{k} n_i e_i^L(mt-1) + e^{MISO}(mt,mr)n$$

$$T_{M\text{-}MISO} = t_s(\sum_{i=1}^{k} \frac{n_i}{b_i^L(mt-1)} + \frac{1}{b^{M\text{-}MISO}(mt,mr)}n)$$

In E_{MIMO} (T_{MIMO}), the first is the energy (latency) needed for local transmission at A, where each nodes with the source information transmits its information to other $mt-1$ nodes, and the second term is the energy (latency) needed for transmitting information I from the A to B using mr virtual $mt \times 1$ MISO links. The constellation size b in each term is selected in the same way described in (2).

3.3.3 Energy and Latency at Other Hops

It is supposed that there are mt nodes in transmission side and mr nodes in reception side cooperating when replaying the information sequence I of n bits. The constellation size b in each term is selected in the same way described in Section 3.3.2.

(1) Traditional SISO Scheme

$$E_{tra} = e^{MIMO}(1,1)n, T_{tra} = \frac{t_s n}{b^0}$$

(2) MIMO Scheme

$$E_{MIMO} = e^L(mt-1)n + e^{MIMO}(mt,mr)n + \sum_{j=1}^{mr-1} e_j^L(1)n_r n_s$$

$$T_{MIMO} = t_s n(\frac{1}{b^L(mt-1)} + \frac{1}{b^{MIMO}(mt,mr)} \sum_{i=1}^{mr-1} \frac{1}{b_j^L(1)} n_r n_s)$$

In E_{MIMO} (T_{MIMO}), the first term is the energy (latency) needed for local transmission at A, where the head node transmits information I to other $mt-1$ nodes, the second term is the energy (latency) needed for transmitting I from A to B using the virtual $mt \times mr$ MIMO link, and the third term is the energy (latency) needed for local transmission at B, where each node other than the head node in B transmits I to the head node.

(3) MISO Scheme

$$E_{MISO} = e^L(mt)n + e^{MISO}(mt,1)n$$

$$T_{MISO} = t_s n(\frac{1}{b^L} + \frac{1}{b^{MISO}})$$

In E_{MIMO} (T_{MIMO}), the first term is the energy (latency) per bit for local transmission at A, where the head node transmits information I to other $mt - 1$ nodes. The second term is the energy (latency) per bit for transmitting I from the A to B using the virtual MISO link.

(4) Proposed Multi-MISO scheme

$$E_{M\text{-}MISO} = e^{M\text{-}MISO}(mt, mr)n$$

$$T_{M\text{-}MISO} = \frac{t_s n}{b^{M\text{-}MISO}(mt, mr)}$$

E_{MIMO} (T_{MIMO}) is the energy (latency) needed for transmitting information I from the A to B using mr virtual $mt \times 1$ MISO links.

3.4 Numerical Results

In the evaluation, we set B to be 10kHz, 20kHz and 30kHz, d from 1m to 16m, D from 20m to 150m, mt and mr from 1 to 8, and $P_b = 10^{-3}$, and each source information size to be 20k bits.

(1) Performance at the first hop

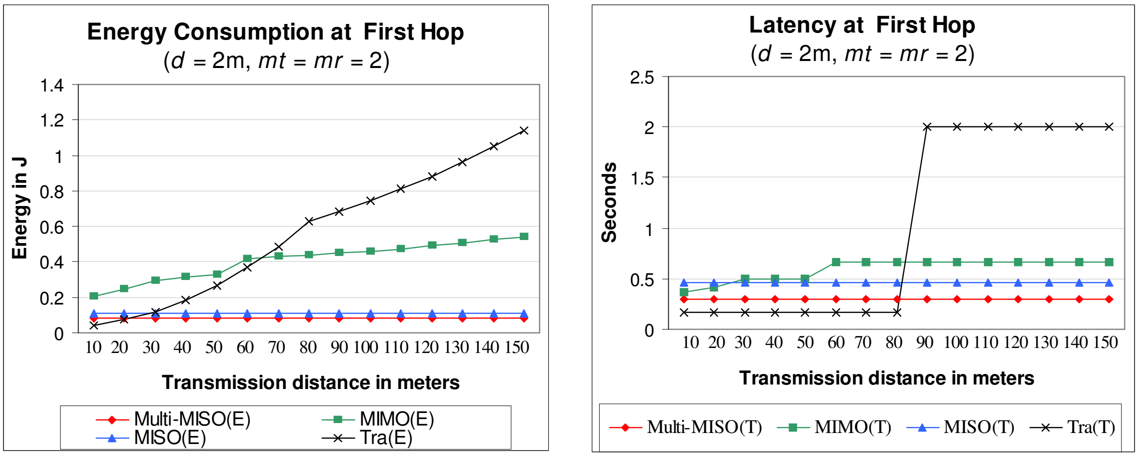
Fig. 4 shows the performance for transmitting two source information in the first hop when B = 20kHz, where in (a) mt = mr = 2, d = 2m, and in (b) mt = mr = 4, d = 10m. The Multi-MISO scheme uses less energy than the traditional non-cooperative scheme when the transmission distance is larger than 20 meters and 50 meters in (a) and (b), respectively. It has less latency than the traditional one when the transmission distance is larger than 80 meters in both (a) and (b). Multi-MISO scheme has the better performance in both energy consumption and latency than any other cooperative MIMO scheme. Fig. 5 shows that the Multi-MISO has less latency and uses less energy for all values of d (the largest distance between cooperative nodes) from 1m to 16m when D = 100m and mt = mr = 2. The graph shows that the same result holds even when d is larger than 16m. Our analysis data shows that the same result holds for other values of D, mt and mr, which means that the proposed Multi-MISO scheme is better than other schemes even when the distance of cooperative nodes is large.

(2) Performance at other hops

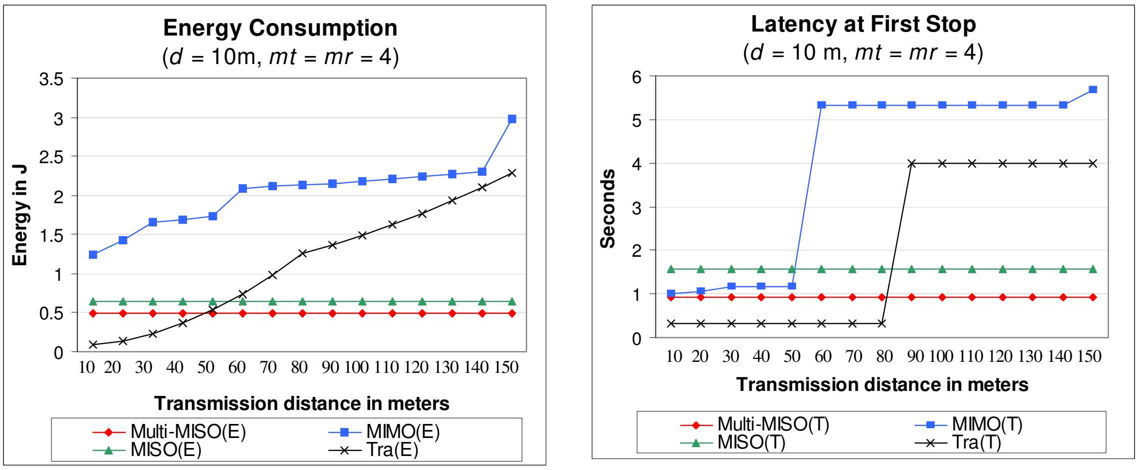
At other hops, the Multi-MISO scheme shows even better performance than at the first hop since it does not need intra transmission between the cooperative nodes at all. Fig. 6 shows the performance for relaying two source information when B = 20kHz, where in (a) mt = mr = 2, d = 2m and in (b) mt = mr = 4, d = 10m. The Multi-MISO scheme has better performance in both energy consumption and latency than the traditional non-cooperative scheme and other cooperative MIMO schemes in all transmission distances. Fig. 7 shows that the Multi-MISO has less latency and uses less energy for all values of d from 1m to 16m when relaying four source information, where D = 100m and mt = mr = 4. The graph shows that the same result holds even when d is larger than 16m. Our analysis data shows that the same result holds for other values of D, mt and mr, which means that the proposed Multi-MISO scheme is better than other schemes even when the distance of cooperative nodes is large.

4 Virtual MIMO Network Formation and Reconfigurable Routing

In this section, virtual MIMO network formation and reconfigurable routing architecture will be described. We assume that the transmission range of WSN nodes can be selected by adjusting their transmission power. A virtual MIMO network is formed from the underlying WSN network by clustering. Each cluster is a virtual MIMO node, where there is a WSN node called *cluster head (CH)*. The *CH*s coordinate cooperative transmission or reception including synchronization in



(a)



(b)

Figure 4: Energy consumption and latency at the first hop: (a) $mt = mr = 2$ and $d = 2$m, and (b) $mt = mr = 4$ and $d = 10$m

the cluster. All *CH*s form a multihop routing backbone, and the cooperative Multi-MISO scheme described in Section 3 is incorporated into each hop transmission. In some research works such as [6, 13], clusters/virtual MIMO nodes are formed (i.e., cooperative nodes are selected) at each transmission link along the route in every routing process, which brings a large computational overhead. In our protocol, the clusters and the routing backbone are formed and initialized only once. They can be used in the entire network lifetime though low cost reconfiguration. The MAC protocol used in the algorithms in this section for avoid the communication collision at link layer is CSMA/CA. The algorithms at each node are described as a sequence of rounds, where each round is assigned by a fix number of timeslot and consists of one transmission and/or one reception and/or local computation.

4.1 Formation of Virtual MIMO Nodes

Clustering and backbone formation algorithms in [11] can be revised for serving the purpose of this paper. We describe more efficient and practical algorithms, though the number of clusters may not be the smallest. Given a WSN, the WSN nodes are self-formed into a set of node-disjoint *d*-clusters

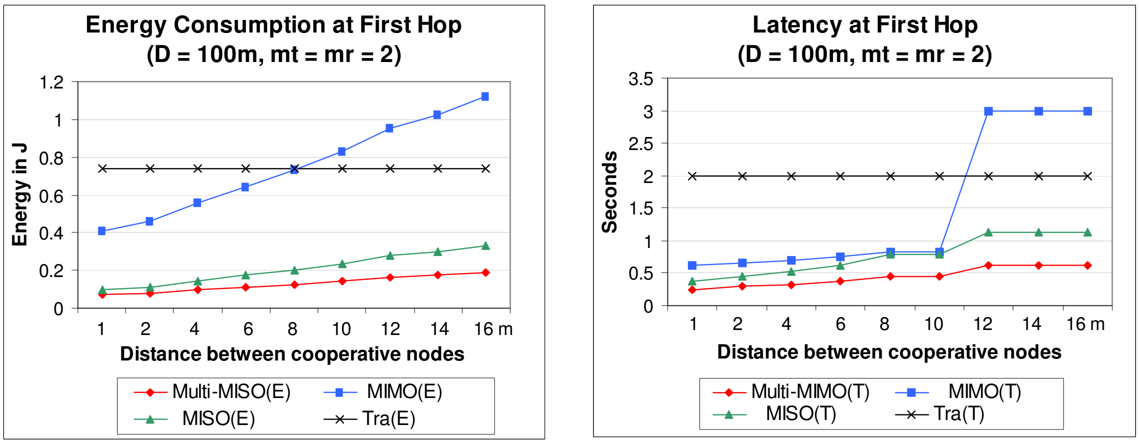


Figure 5: Energy consumption and latency at the first hop, when $mt = mr = 2$, $D = 100$m, and d changes from 1m to 16m

by using the following algorithms. In the algorithm, each node u declares the neighbor node v who has the smallest *ID* to be u's *CH*. However, if there is any other node who declares u as its head, u changes itself to be a *CH*.

Algorithm 1 Formation of d-Clusters

Input: a WSN of n nodes, and cluster diameter d.

Output: node-disjoint clusters, where in each cluster one node is *CH* and others are cluster members (*CMs*), the *CH* has a member list with member IDs and other information such as battery levels, the members have their *CH* ID, and the distance of two nodes in the cluster is not larger than d.

Each node u executes the following rounds :

Round 1

u broadcasts hello message (u, "hello") to its neighbors at a random timeslot in transmission range $d/2$, and receives the messages from its neighbors.

Round 2

If u receives messages (v, "hello"), it selects a node v which has the smallest ID from all received messages, and sets v to be u's *CH*. Then u broadcasts is-member message (u, v, "*is-member*") with u's other required information such as the battery level at a random timeslot in transmission range $d/2$, and u receives the messages from its neighbors.

Round 3

If u receives is-member messages (v, u, "*is-member*") which means v is u's member, u sets itself to be a *CH* and adds every v and v's other information into u's member-list. Then u broadcasts head-declare message (u, "head-declare") at a random timeslot in transmission range $d/2$, and receives the messages from its neighbors.

Round 4

If u receives head-declare messages (v, "*head-declare*") and u is a CH, u deletes v from its member-list if v is in it.

Round 5

If node u has no member, it sets itself to be a *CH*.

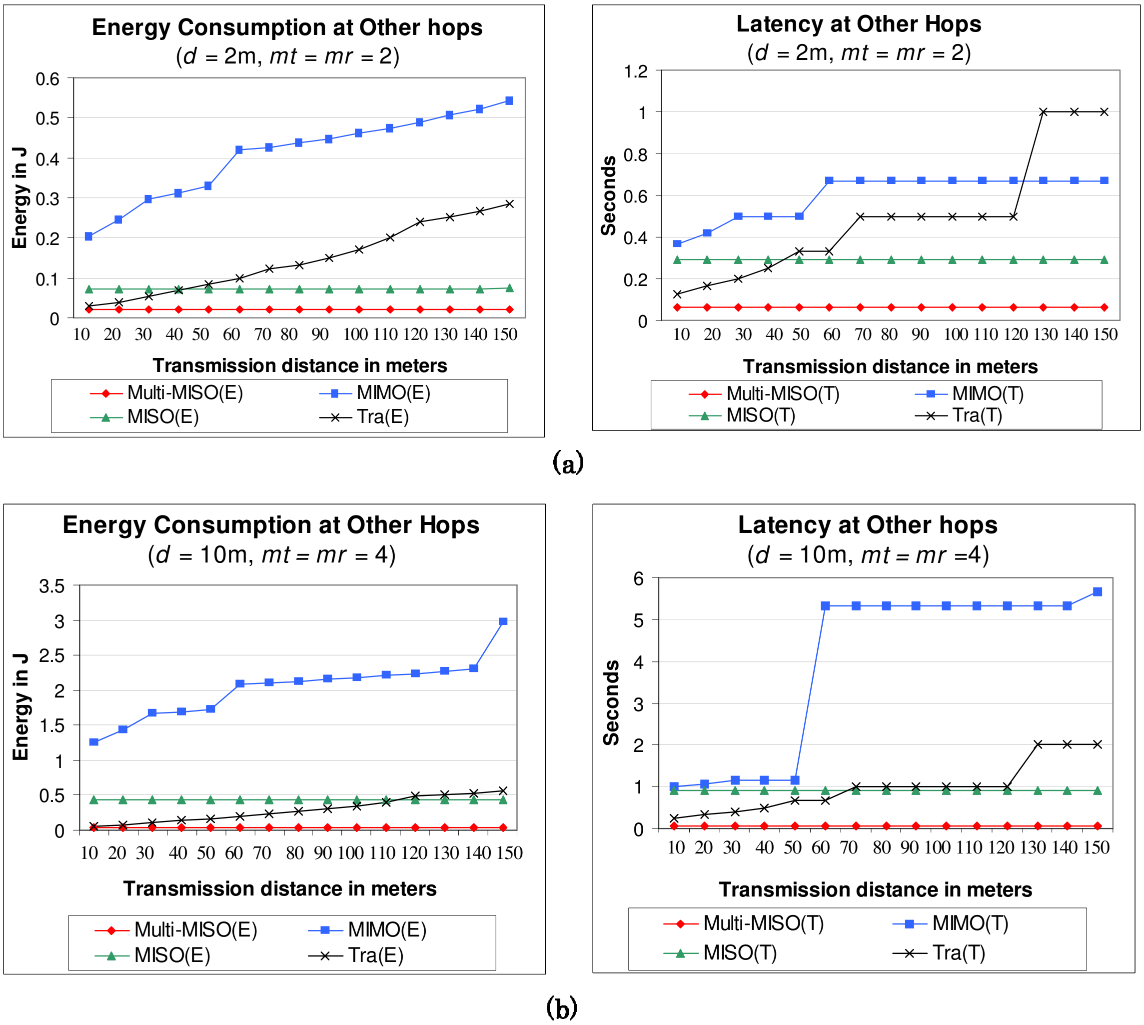


Figure 6: Energy consumption and latency at the other hops: (a)$mt = mr = 2$ and $d = 2$m, and (b) $mt = mr = 4$ and $d =$10m

According to Algorithm 1, the *CH* in a cluster is in the transmission range $d/2$ with its members. Therefore, the distance of any two nodes in the cluster is not larger than d. The algorithm needs only O(1) round.

4.2 Routing Backbone and Multi-MISO links

The routing backbone is a spanning tree of the *CH*s and it is formed by a distributed breadth-first-search based algorithm. The sink s starts the algorithm by broadcasting a "find-children" message. Each node u sends a response back to s when u gets the message. When s get u's response, s adds u into its neighbor list. At same time, u broadcasts a "find-children" message to find u's children. This procedure will continue until all the nodes join to the backbone tree.

Algorithm 2 **Formation of the Routing Backbone**

Input: m *CH*s, sink s, and transmission range D, diameter L of the underlying WSN.

Output: A spanning tree of the m *CH*s and the sink, where the sink is the root, each *CH* knows its parent and its children and their information in the backbone, the distance between two

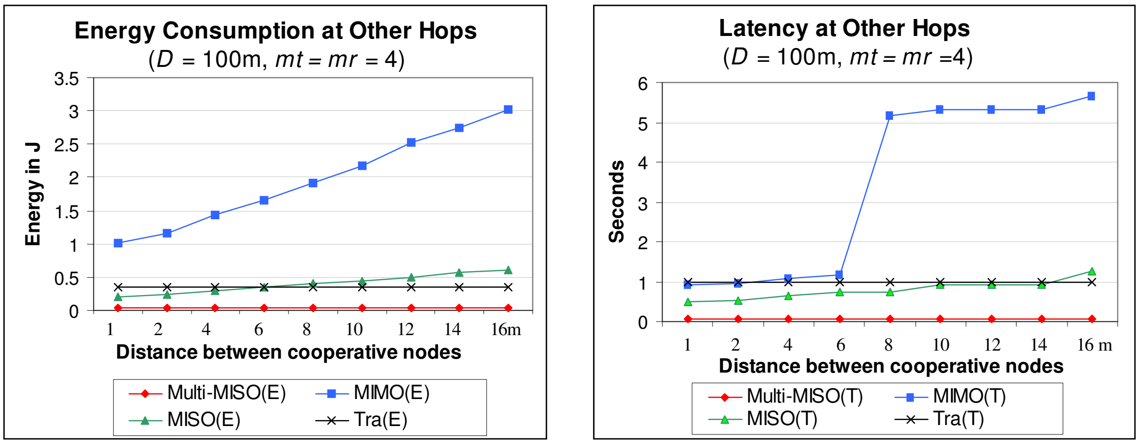


Figure 7: Energy consumption and latency at the first hop, when $mt = mr = 4$, $D = 100$m, and d changes from 1m to 16m

neighboring *CH*s in the backbone is not larger than D.

Sink s **executes the following rounds** :

Round 1
Sink s broadcasts find-child message (s, "find-child") in transmission distance D to its neighboring *CH*s, and receives the messages from the neighbors.

Repeat the following Round 2
If s receives messages (u, s, "is-child"), s adds every u to its children list.

Each *CH* u **sets its status to be "wait-parent" and executes the following rounds** :

Repeat the following Round 1 and Round 2

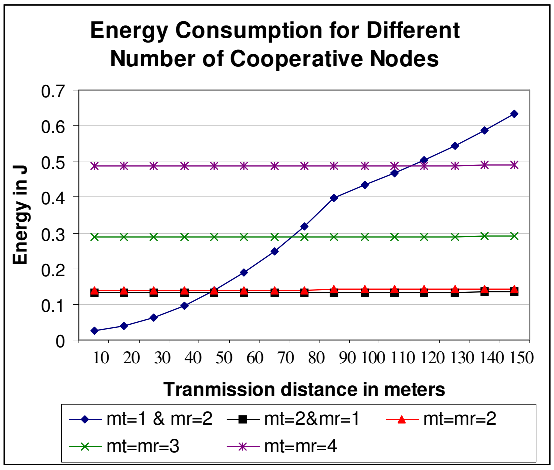
Round 1
If u receives find-child messages (v, "find-children") and u's status is "wait-parent", then do the following steps:

(i) u sets v to be its parent. If u receives more than one message, u selects one v which is the farthest from u from all received messages (it can be implemented by selecting the message which has the weakest signal but above the predefined threshold). Then u changes its status to be "find-children".

(ii) u broadcast is-child message (u, v, "is-child") and find-children message (u, "find-children") at a random timeslot in transmission distance D, and receives the messages from the neighbors.

Round 2
If u received is-child messages (v, u, "is-child") and u's status is "find-children", u adds every v to u's children list, and receives the messages from the neighbors.

In the above algorithm, for any node u of *CH*s or the sink, the distance u and u's any grandchild v is larger than D, otherwise v would be u's child. Therefore, the backbone can be built in $2L/D$ rounds. In the routing backbone, multiple MISO links are defined at each edge between cluster A and cluster B. According to the numerical analysis, the optimal value of mt and mr (i.e., the number of cooperative nodes at transmission side and reception side) varies from one to six depending on d, D, P_b, and B. In other words, the optimal number of the cooperative nodes in a cluster is not larger than six no matter what values of d, D, P_b, and B are. Fig. 8 shows the latency and energy consumption in the Multi-MISO scheme for different values of mt and mr when relaying four source information of 2k-bit at second hop, where d = 10m, D = 100m, $P_b = 10^{-3}$ and B = 20kHz. In this case, $mt = 2$ & $mr = 1$ and $mt = mr = 2$ are the optimal ones. Suppose that a small table of optimal values of mt and mr is saved at each head node.



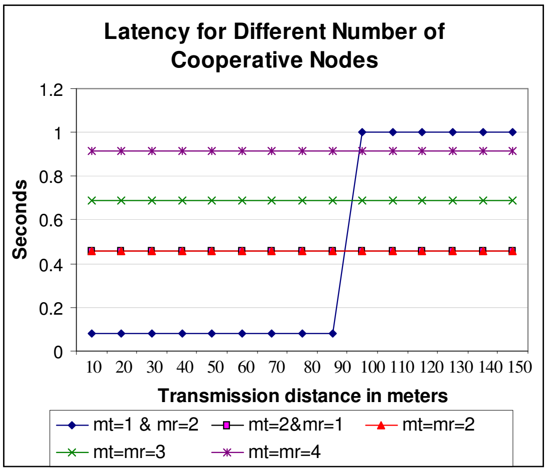


Figure 8: Energy consumption and latency for different number of cooperative nodes at transmission side and receptions side, where D = 100m and d = 10m

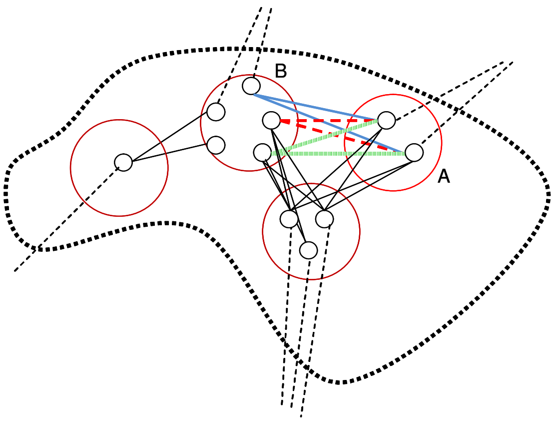


Figure 9: Multiple MISO links are defined at each edge of the backbone tree

To form multiple MISO links at the edge from cluster A to cluster B, the head of A selects the number of $a = min$ (the number of nodes in A, optimal number of cooperative nodes) cooperative nodes from A with the highest battery levels, and the head of B selects b cooperative nodes similarly. In this way, b multiple $a \times 1$ MISO links are defined at the edge from A to B. In Fig. 9, two cooperative nodes are selected in cluster A and three cooperative nodes are selected in cluster B. Therefore, 3 multiple 2×1 MISO links are defined at the edge from A to B.

4.3 Network Reconfiguration

We suppose each CH u maintains the following information: (1) u's members IDs and u's battery power level, and (2) the transmission distance between u and each neighboring CH v (it is initialized as D) in the routing backbone.

4.3.1 Head-rotation and link-jumping

Algorithms *head-rotation* and *link-jumping* are designed for maximizing the network lifetime. Head-rotation is invoked when a *CH* u runs out of battery or needs to move out of the network. In the head-rotation operation, u selects a *CM* v in this cluster with the highest battery level to replace u. If the battery levels of all *CM*s are lower than the battery threshold, link-jumping is invoked. In the link-jumping operation, u's children and u's parent in the backbone get connected by extending their transmission distance. Link-jumping is the function enabled by MIMO technology. As we see in Section 3, in a traditional non-cooperative SISO scheme, the energy consumption increases largely when transmission distance increases. However, in a cooperative MIMO transmission scheme, the energy consumption doesn't increase very much when the transmission distance increases.

Algorithm 3 Head-Rotation (u: *CH* node, e: energy threshold, d: transmission distance in the cluster)

1. u checks its battery energy;

2. If u's energy level is lower then e and there is no *CM* whose energy level is larger than e, u invokes link-jumping operation;
else u selects a *CM* v with the largest energy level in u's cluster; u broadcasts a head-rotation request (u, v, "head-rotation") with the member list in transmission distance d.

3. When other node v receives the request and the member list from u, v changes its status to be *CH*, deletes u from the member list, and updates the cooperative nodes in its cluster. When any *CM* w other than v relieves the message, w changes v to be its *CH*.

Algorithm 4 Link-Jumping (u: *CH* node)

1. u broadcasts a link-jumping request (u, v, "link-jumping") with u's children list in the backbone in transmission distance d', where v is u's parent in the backbone and $d' = \max\{d(u,w)|w$ is u's neighbor in the backbone and $d(u,w)$ is the transmission distance of u and w which is initialized as $D\}$.

2. When u's neighbor w receives the link-jumping request, w sets the transmission distance of v and w to be $d(w,v) = d(w,u) + d(u,v)$. If w is u's child, w sets u's parent v to be w's parent; else (i.e. w is v) w deletes u from w's children list and add u's children into the children list. w updates the cooperative nodes in its cluster.

In algorithm Link-Jumping, in order to reach every neighbor in the backbone, u sends the request using the largest transmission *distance* between u and its neighbors. Head-rotation and link-jumping can be completed locally in O(1) round.

4.3.2 Reconfiguration functions

Node-joining and node-leaving operations are designed for reconfiguring the virtual MIMO network. In the node-joining operation, new node *new* is supposed neighboring with at least one node of the backbone in transmission range D. If *new* can find a *CH* in transmission distance $d/2$, *new* becomes a *CM* of this *CH*. Otherwise, *new* becomes the *CH* of a new cluster, and *new* selects one of the neighboring *CH*s in transmission distance D to be its parent in the backbone.

Algorithm 5 Node-Joining (*new*: node for joining)
Repeat the following rounds until *new* finds a parent in the backbone tree

Round 1
Node *new* broadcasts a cluster-join request (*new*, $d/2$, "join") in transmission distance $d/2$. When a *CH* u receives the request, u broadcasts a head-declare message (u, *new*, "head-declare") at a random time-slot in transmission range $d/2$.

Round 2

If *new* receives the head-declare messages (u, *new*, "head-declare"), it sets its status to be *CM* and select one u from the messages to be its *CH*. *new* broadcasts a child-declare message (*new*, u, "child-declare"). When u receives the child-declare message, u adds *new* to u's member list. Otherwise (*new* forms a new cluster in which new is the *CH* and the only node), *new* broadcasts a backbone-join request (*new*, D, "join") in transmission range D. When a *CH* u receives the request, u broadcasts message (u, *new*, "parent-declare") at a random timeslot in transmission range D.

Round 3

When *new* receives the messages (u, *new*, "parent-declare"), *new* selects one u from the messages to be *new*'s parent in the backbone, *new* sets itself to be the only one in the cooperative nodes for the edge between *CH* w and *CH new*, and then broadcasts the message (*new*, u, "child-declare"). When u receives the message (*new*, u, "child-declare"), u sets *new* to be its child in the routing backbone, and u updates the cooperative nodes for the edge between *CH* u and *CH new*.

Assume that a node *lev* is running out of the battery or leaving the WSN. The following algorithm reconfigures the clusters and the routing backbone.

Algorithm 6 Node-Leaving (*lev*: node for leaving)

If *lev* is a *CM*, *lev* broadcasts a request "*lev* is leaving" using transmission distance d, and *lev* leaves (move out or turn off the power). When *lev*'s *CH* receives the request, it deletes *lev* from its member list and updates the cooperative nodes in the cluster.

If *lev* is a *CH*, *lev* invokes head-rotating function (when the function finishes, either a *CM* will replace *lev* if there is at least one *CM* whose energy level is larger then the energy threshold, or *lev*'s children and *lev*'s parent get connected by invoke link-jumping function), and *lev* leaves.

In the above algorithms, Node-Joining and Node-Leaving can be completed locally in O(1) rounds. Node-leaving used to be a tough task in the reconfiguration of a cluster-based WSN [11]. However, by using head-rotation and link-jumping enabled by MIMO technology, the task can be completed locally in O(1) round.

4.4 Routing Algorithms

The routing algorithms for broadcast, data gathering, and unicast on the routing backbone are similar to those in [2, 11]. In the broadcast, the data from the sink is delivered to every node through the backbone using distributed depth-first search approach or breadth-first search approach in top down manner. In the data gathering, the data are gathered using the routing backbone from children to the parent in bottom up manner. In the unicast, the route for data transmission between two nodes u and v is built by constructing a route from u to the root and the root to v.

4.5 Simulation and Experimental Results

In this section, energy consumption and latency are evaluated when multiple source data are relayed from a virtual MIMO node to the sink in the virtual MIMO network. The underlying WSN network is formed by randomly deploying 5,000 to 17,000 WSN nodes in a 400m×400m field. Clusters/Virtual MIMO nodes and the routing backbone are formed by the algorithms in Section 4.1 and 4.2 when d and D are given, where d is the of the diameter of clusters/virtual MIMO nodes and D is the the length of the edges (i.e., the transmission distance between virtual MIMO nodes) in the backbone. The average size of the clusters/MIMO virtual nodes and the average number of hops from a leaf to the sink in the backbone depend on the values of d and D.

In the simulation, four source data with 20k-bit each in a randomly selected cluster are relayed back to the sink, and the number of cooperative WSN nodes at each cluster on the relaying route is set to be $min(6, \text{size of the cluster})$. The bandwidth and ERB are set to be $B = 2$kHz and $P_b = 10^{-3}$.

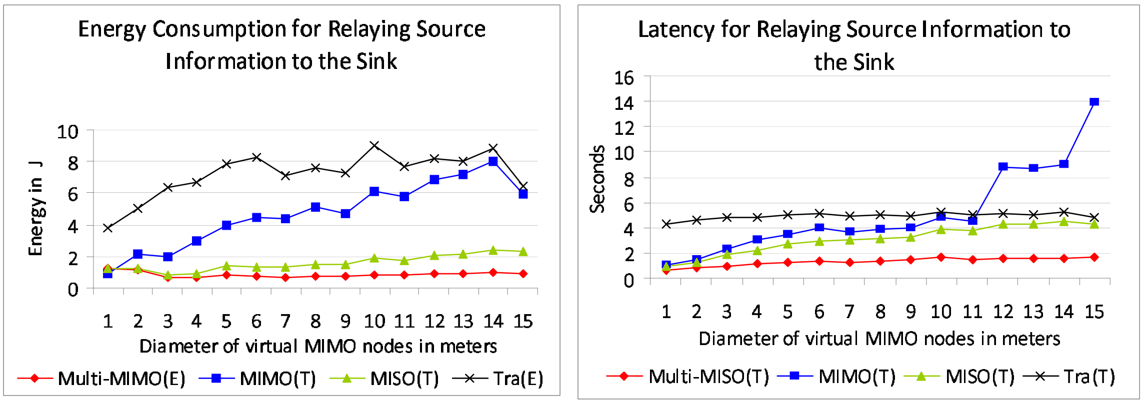


Figure 10: Energy consumption and latency in the virtual MIMO networks, where $D = 100$m and d changes from 1m to 15m

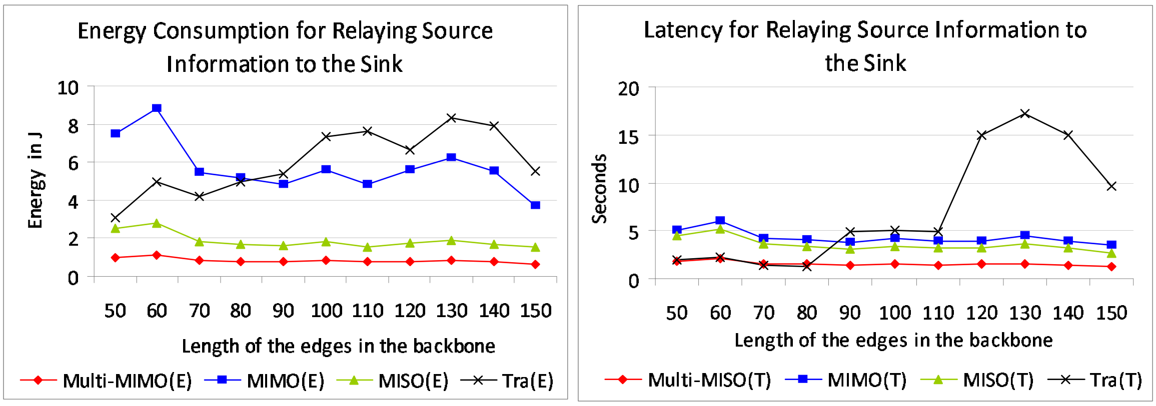


Figure 11: Energy consumption and latency in the virtual MIMO networks, where D changes from 30m to 150m

According to the simulation results, the proposed cooperative design better performance than the traditional non-cooperative design and other cooperative design in all instances. Fig. 10 shows the energy consumption and latency in the virtual MIMO networks built on a WSN with 17,000 nodes, where $D = 100$m and d changes from 1m to 15m. In the virtual network configuration, the average number of hops from a leaf to the sink is 2.47, and the average size of the clusters/virtual MIMO nodes is 1.2 when $d = 1$m and it is 6.4 when $d = 15$m. The proposed Multi-MIMO based approach needs less energy and latency than the traditional non-cooperative approach and other cooperative approaches for all value of d. Notice that in order to fairly compare the performance, energy consumption and latency in all approaches are optimized at each hop by adjusting constellation size b as described in Section 3, though they may not be optimized in the original works. Since the larger d implies more energy needed in intra communication in cooperative approaches and MIMO based approach requires large amount of intra communication at virtual MIMO nodes, among Multi-MISO, MISO and MIMO based approaches, the MIMO based approach is worse than other approaches when d is larger than 1m. In Fig. 10, the values of energy and latency fall locally sometimes, e.g. at $d = 9$m. The reason can be the location of the source information. One hop closer to the sink implies less energy consumption and latency in the relay process. Other parameters in cooperative transmission can also change the energy consumption and latency. Fig. 11 shows the performance in the virtual

MIMO networks built on the same WSN, where $d = 10$m and D changes from 30m to 150m. In the network configuration, the average number of hops from a leaf to the sink is 5.83. Specifically, the average number of hops from a leaf to the sink is 10 when $D = 30$m and it is 2 when $D = 150$m. The proposed Multi-MIMO based approach has the better performance both on energy consumption and latency than other approaches for all value of D.

5 Conclusion

In this paper, a cooperative Multi-MISO transmission scheme, virtual MIMO network formation and reconfiguration algorithms and a cooperative routing backbone have been cross-layered designed for WSNs to jointly achieve required reliability, energy efficiency and delay reduction. The proposed transmission scheme minimized intra transmissions among the cooperative nodes. It can save energy saving and reduce delay at transmission links even when the diameters of virtual MIMO nodes is large. With a required reliability, energy and latency can be simultaneously optimized along the route in a cooperative relay. Given a WSN, the virtual MIMO radio network and routing backbone is formed and initialized only once. With low cost reconfiguration functions, they can stay in use during the whole network lifetime. The numerical analysis and computer simulation show that the proposed approach achieved the better performance than the traditional SISO non-cooperative approach and other virtual MIMO cooperative approaches.

Acknowledgement

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