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Energy Efficient Clustering Mechanism for Virtual MIMO Communication in Wireless Sensor Networks

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Abstract
Multi-input multi-output (MIMO) is a technique for increasing the link throughput, extending the transmission range, and reducing energy consumption. In wireless sensor networks (WSNs), even if each node is equipped with a single antenna, it is possible to group several nodes to form a virtual antenna array, which can act as the transmitting or receiving end of a virtual MIMO (VMIMO) link. An energyefficient clustering and power management schemes for VMIMO operation is proposed. A comprehensive protocol, called cooperative MIMO(CMIMO), involves clustering the WSN into several clusters, each managed by up to two cluster heads(CHs); a master CH(MCH) and a slave CH(SCH) is established. The MCH and SCH collect data from their cluster members during the intra-cluster communications phase and communicate these data to neighboring MCHs/SCHs via an inter-cluster VMIMO link. CMIMO achieves energy efficiency by proper selection of the MCHs and SCHs and adaptation of the antenna elements and powers in the inter-cluster communications phase.

Keyword: Wireless Sensor Networks, Energy Efficient, Virtual MIMO, Power Management

1. Introduction

Nodes in wireless sensor networks (WSNs) are typically powered by small batteries. Replacement or recharging of these sensors is often difficult due to two reasons: (1) Sensors are deployed in large numbers, making the process of manually recharging them expensive and time consuming, and (2) in some applications, such as reliefandrescue and battlefields, it may be infeasible to reach the sensors once they have been dispatched. Consequently, improving the work, we focus on diversity gain, leaving the exploitation of other types of gain for future research.

A typical MIMO system requires multiple antennas at the transmit and/or receive end of a link. However, in dense topologies such as WSNs, it is also possible to group two or more singleantenna nodes to form a cooperative (virtual) multiantenna node. Forming such a virtual node requires sensor nodes to exchange information and decide on the data to be transmitted cooperatively.

To ensure that the energy overhead of information exchange is manageable, only those nodes that are geographically close to each other should be part of the virtual node. In general, data obtained by sensor nodes in dense WSNs exhibit a high degree of redundancy, which can be significantly reduced by means of aggregation/fusion [3]. Data aggregation is facilitated by node clustering, which organizes the network into a connected hierarchy [4]. In the context of WSNs, clustering involves grouping nodes and electing a cluster head (CH) such that the nonCH nodes of a cluster can directly communicate with their CH. CHs forward aggregated data to the sink directly or via other CHs. Topologically, the collection of CHs in the network forms a connected dominating set.

In this paper, we propose a distributed MIMOadaptive energyefficient clustering/routing protocol, coined cooperative MIMO (CMIMO), for multihop WSNs. According to this protocol, each cluster has up to two CHs, which are responsible for intercluster communications. Clustering is done based on the remaining battery lifetime (RBL), neighbor proximity, and network density. The rationale for adopting these criteria is to construct cooperative MIMO links whose effect is as close as possible to actual MIMO systems (with two antennas per node) and that have manageable overhead.

It should be noted that although this work focuses on clusters with at most two CHs per cluster, the proposed methodology is actually applicable to any number of CHs. Specifically, the proposed procedure and criteria for network clustering and coordination of the cooperation process do not depend on the number of cooperating nodes. However, optimizing this number (and selection) leads to a combinatorial problem of high computational complexity. Thus, to maintain a reasonable computational overhead, we limit our treatment to two CHs per cluster.

The rest of the paper is organized as follows. Section 2 provides related work. We describe the CMIMO protocol in Section 3. The system model and the energy consumption analysis are provided in section 4. In Section 5 we discuss some issues related to the design of CMIMO, including connectivity, synchronization, reclustering, and medium access control. The performance of the proposed protocol is evaluated via simulations in Section 6. Section 7 discusses the main conclusions of this paper as well as some generalizations and extensions

2. Related Works

In this section, we describe recent works on VMIMO systems and node clustering in WSNs. VMIMO was first proposed by Dohler in [7,8] in the form of virtual antenna arrays. Then, several VMIMO systems for WSNs have been proposed in the literature (e.g., [6,9,10]). In these systems, several single antenna nodes cooperate on information transmission/reception to achieve energyefficient communications. The authors in [6] studied a cooperative MIMO scheme with Alamouti code for single hop transmissions in WSNs. They analyzed the best modulation and transmission strategy to minimize the total energy consumption required to send a given number of bits. The results showed that over certain distances, both the total energy consumption and the total delay can be reduced, even when the energy and delay costs associated with the local information exchange are taken into account.

A cooperative MIMO scheme for delay and channel estimation was proposed in [9]. This scheme uses two transmitting sensors and space–time block codes to provide transmission diversity in distributed WSNs. Full diversity and full rate were achieved, which enhance power/bandwidth efficiency and reliability. It should be noted that neither antenna arrays nor transmission synchronization were used. In [10] energy efficiency and training overhead of cooperative MIMO WSNs were analyzed. The author compared the performance of such systems with that of SISObased WSNs. The dependence of energy efficiency on the coherence time of the fading process and on the communications distance was considered. The incorporation of data aggregation into cooperative MIMO was recently considered [11]. Multihop VMIMO communications with distributed space–time coding were investigated in [12].

All the above VMIMO schemes exploit the diversity gain using distributed space–time codes. In [13] the author exploited the multiplexing gain of VMIMO to reduce the cooperation overhead and the circuit energy consumption.

VMIMO operation was realized by using the Vertical Bell Laboratories Layered Space–Time (VBLAST) technique. The scheme in [13] also conserves significant energy, compared with SISObased schemes. Using VBLAST for spatial multiplexing, the authors in [14] optimized MIMO's operation under power and delay constraints.

In all the abovementioned contributions, clustering and multihop routing were not taken into consideration, which limits the scalability of these schemes in large WSNs. The authors in [15] argued that by jointly considering the clustering and routing problems, one can reduce the signaling overhead of the routing task, hence conserving significant energy.

Many clustering schemes were proposed for WSNs, which can be classified based on two criteria [16]: (1) The parameters used for electing CHs, and (2) the execution nature of the clustering algorithm (probabilistic or iterative). Some clustering schemes under the first category use the node ID to elect CHs. Others favor nodes with larger degrees. Some other schemes were proposed for controlling the network topology by exploiting node redundancy. Regarding the second category, the execution of a clustering scheme can be carried out at a centralized authority (e.g., a base station) or in a distributed way at local nodes. In iterative clustering schemes, a node waits for a specific event to occur or certain nodes to decide their role (e.g., become CHs) before making a decision. This results in some delay in the convergence time. On the other hand, probabilistic (or randomized) clustering schemes ensure rapid convergence while achieving some favorable properties, such as balanced cluster sizes.

DCA [17] is one of the popular clustering schemes, which clusters nodes in an iterative way. In DCA, nodes divide themselves into groups according to a weightbased criterion. The main assumptions behind DCA are: (1) The network topology is static, and (2) each transmitted message is correctly received by all neighbors within a specific duration of time. As the first assumption is reasonable for WSNs, the second one opens several issues with respect to reliability and collisions.

HEED [18] is a clustering scheme that does not make any assumptions about the presence of infrastructure or about node capabilities, other than the availability of multiple power levels in sensor nodes. The key idea behind this scheme is to periodically select CHs according to a hybrid metric that combines the node's RBL and a secondary parameter, such as node degree. The authors showed that with appropriate bounds on node density and intra/intercluster transmission ranges, HEED can asymptotically almost surely guarantee connectivity of clustered networks..

3. The CMIMO Protocol

3.1. Overview

CMIMO is a distributed protocol for clustering and virtual MIMO communications that aims at minimizing the total energy consumption (transmission plus circuit energies) in a multihop WSN. Each cluster is managed by one or two CHs: A master CH (MCH) and a slave CH (SCH). The two CHs operate as a cooperative multiantenna node for intercluster communications (see Fig. 1). The operation of CMIMO consists of three main phases: Cluster formation, intracluster communications, and intercluster communications. We discuss these phases in detail in the next subsection. In brief, cluster formation is a distributed process for selecting the CHs of each cluster (the MCH is mandatory whereas the SCH may or may not be present) and associating nonCH nodes with corresponding MCH/SCH pairs. During intracluster communications, the MCH is responsible for aggregating data sent by other nodes in its cluster and exchanging these data with the SCH, so that the two may operate as a cooperative multiantenna node. Intercluster communications is carried out by forwarding data from the CHs of one cluster to the CHs of a neighboring cluster (or directly to the sink). An energyefficient routing algorithm is executed over the topology of virtual nodes to determine an endtoend intercluster path that minimizes the total energy consumption. This is done by running Dijkstra's algorithm with the weight of a link taken as its total energy consumption. It should be noted that for each virtual MIMO link, the MCH (or the MCH and SCH) of the receiving cluster selects the optimal transmission mode and transmission power for communication with other CHs.

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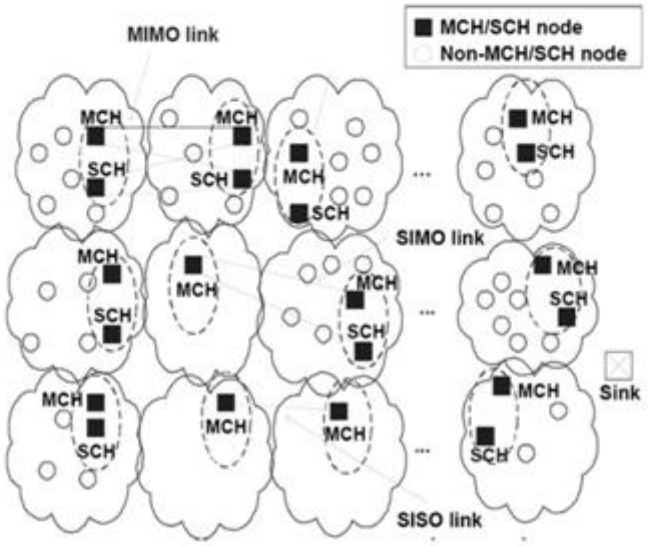

Fig 1. Example topology of a clustered WSN with intercluster virtual MIMO links.

3.2. Operational details

3.2.1. Cluster formation

The cluster formation process consists of the following steps:
Step 1: Neighborhood discovery. In this step, each node uses a CSMA/CA scheme to contend for the channel. Once a node v succeeds in accessing the channel, it sends a ‘‘hello’’ message at a power level P_{intra} to discover its 1hop neighbors. This hello message carries the following information: node ID, its RBL (or a metric that indirectly reflects this value), and a list of known neighbors (nodes that v has received hello messages from). Node v sends a hello message whenever any of these two events occurs: (1) v receives a hello message from a node, say u, that is not already in v’s neighbor list, or (2) v receives a hello message from an already known neighbor u but u’s hello message does not include v as a neighbor. In both cases, v broadcasts an updated hello message.
Step 2: Selecting MCHs. After neighborhood discovery is completed, MCHs are selected. Because MCHs do more work than nonMCH nodes (e.g., collecting, aggregating, and forwarding data), the selection criterion for MCHs is the node’s RBL. It should be noted that this criterion has been also used in several previously proposed clustering protocols (e.g., [18]).
Step 3: Selecting SCHs. The next step is to associate an SCH with each MCH, if possible. The purpose of having SCHs is to achieve VMIMO diversity gain during the intercluster communications phase by constructing cooperative multiantenna nodes. We consider three possible criteria for SCH selection. The first one is based on the degree of overlap between the neighbor lists of the MCH and SCH.
Step 4: Cluster membership. The final step in the clusterformation phase is to have nonCH nodes decide on which cluster to join. Because every nonCH node is a neighbor of one or more MCHs, such a node attempts to associate itself with its closest MCH by sending a ‘‘membership request message’’ at a power level P_{intra}.

3.2.2. Intracluster communications

Each nonMCH node transmits its data to the MCH at power level P_{intra} according to the TDMA schedule. After that, the node goes to sleep until its next transmission cycle. MCHs and SCHs do not go to sleep, as they may still receive data from other clusters. Upon receiving data from the SCH and nonCH nodes, an MCH aggregates the received data, and sends the aggregated data to its SCH during an assigned TDMA slot.
As a result, both the MCH and SCH will be ready for the intercluster communications phase. Note that nonCH nodes send their data to the MCH only (and not to the SCH) because even if the cluster has an SCH, some nonCH nodes may not have the ability to directly communicate with it. For example, in Fig. 3, node 8 is a nonCH node that cannot directly communicate with its SCH (node 6). However, by design all nonCH nodes must be able to directly communicate with their MCH.

Step 1: Neighborhood discovery
(1) Each node contends for the channel using CSMA/CA.
(2) Every node sends a “hello" message with its ID, its RBL, and a list of its neighbors.
(3) A node sends new “hello" messages whenever there is a change in its connectivity information.
Step 2: Selecting MCHs
(1) The node that has the highest RBL in its neighborhood declares itself as an MCH.
(2) ID-based criterion is used to break ties in selecting MCHs with the same RBL.
(3) A node that has the highest RBL among its *undecided* neighbors becomes an MCH.
(4) Any node that hears from an MCH does not compete for the role of an MCH.
Step 3: Selecting SCHs
(1) Each MCH sends an “SCH invitation message" to the node whose neighbor list overlaps the most with that MCH’s neighbor list.
(2) The invited node waits for a duration of time (ζ) before making its decision.
(3) An invited node associates itself with the closest MCH and responds with an “SCH acceptance message."
(4) The MCH confirms this association via an “SCH confirmation message."
(5) Non-CH nodes go to cluster membership step.
Step 4: Cluster membership
(1) Every non-CH node asks its closest MCH to join its cluster via a “membership request message."
(2) The MCH sends its “membership list message" periodically.
(3) The “membership list message" includes the TDMA schedule that the SCH and non-CH nodes should follow in their intra-cluster data communications.

Fig. 2. Summary of the clustering procedure in CMIMO.

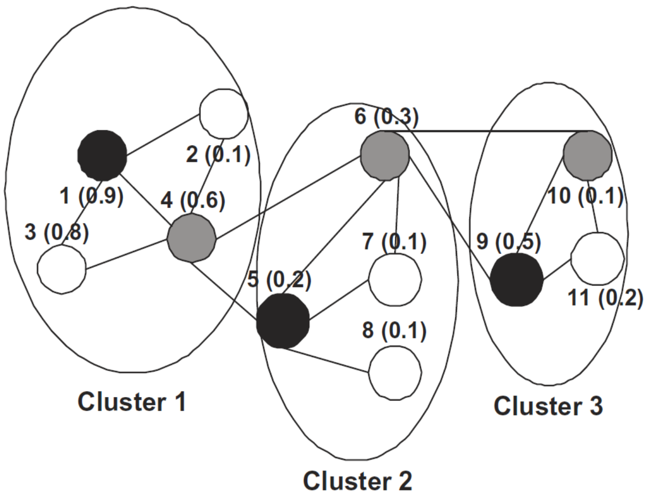

Fig.3. WSN topology after step 4 (MCHs are indicated by black circles and SCHs are indicated by gray circles).

3.2.3. Intercluster communications with virtual MIMO

We now discuss how to establish an intercluster VMIMO link. The purpose of this phase is to decide on the appropriate transmission power and antenna mode to use. Note that at this point, each MCH is already aware of its neighboring MCHs (at power level P_{inter}) following the overhearing of the ‘‘SCH confirmation messages’’ in step 3 of the clusterformation phase. For a static WSN and a given clustering configuration, steps 1 through 6 of this phase are executed only once. These steps can be viewed as a ‘‘training process’’, whose outcome is the optimal VMIMO configuration for various intercluster links. The operational details for establishing cooperative MIMO links are as follow

Step 1: If the MCH of a given cluster wishes to establish VMIMO links with adjacent clusters, it accesses the channel using the CSMA/CA scheme. Once it acquires the channel, the MCH broadcasts a channelprobingrequest (CPREQ) packet at a power level $P^{ð}_{CPREQ}{}^{1Þ}$. One purpose of this CPREQ packet is to notify the MCH/SCH of the receiving clusters of the presence or absence of an SCH at the source cluster. The MCH’s CPREQ will also be heard by the SCH of the transmitting cluster, so it knows when to send its own CPREQ.

Step 2: If the source cluster has an SCH, then after the source MCH sends its CPREQ packet, the source SCH will follow with its own CPREQ. This CPREQis sent at $P^{ð}_{CPREQ}{}^{2Þ}$, and is used to obtain the channel state information (CSI) between the source SCHand the destination SCH and MCH. The CPREQ packets also facilitate the determination of an energyefficient path between the source CHs and the sink, as explained later. An example that illustrates the CPREQ broadcasts between two clusters (steps 1 and 2) is shown in Fig. 4.

Step 3: Upon receiving the two CPREQ packets, the receiving MCHs and SCHs estimate the CSI between the source MCH/SCH and the receiving MCH/SCH and communicate such information to each other. From that, the receiving CHs calculate the minimum power needed to communicate between the CHs of the transmitting and receiving clusters using one of four possible modes (SISO, MISO, SIMO, MIMO). Such power determination is explained in Section 4.

Step 4: The MCH and SCH in each neighboring cluster determine the optimal transmission mode that minimizes the total energy (which includes both transmission and circuit components) among the four modes. Each receiving MCH then sends this information back to the source MCH/SCH (and also to the receiving SCH) via a channelprobingresponse (CPRES) packet. It should be noted that the process of finding the optimum transmission mode via exchanging the CPREQ and CPRES packets is done once (not on a perpacket basis), as the network is assumed to be stationary.

Step 5: A graph of virtual intercluster links is then constructed, where each link in this graph represents the transmission mode that requires the least amount of energy, as shown in Fig 5. Information about the selected transmission power and mode for each link is flooded throughout the network, so that each cluster will eventually have a complete knowledge of all links’ weights, which will be used as input to the path selection algorithm.

Step 6: A minimum energy routing algorithm is then executed by the source MCH on the intercluster topology of virtual nodes. This algorithm consists of two steps. In the first step, all pairs of virtual nodes that can directly communicate at P_{inter} using at least one of the four modes are determined. In the second step, we run Dijkstra’s algorithm with the weight of a link taken as its total energy value determined from the first step. The returned path has the minimum total energy among all possible paths between the source CHs and the sink.

Step 7: Whenever a given cluster has data to transmit to the sink, its CHs transmit their aggregated data to the CHs of the nexthop cluster using the negotiated power and mode. Specifically, the MCH of the source cluster accesses the medium using CSMA/CA and sends an RTS packet. Upon receiving the RTS, the MCH of the receiving cluster responds with a CTS packet that serves as a synchronization signal for the two CHs of the source cluster, so that they transmit their data simultaneously to achieve MIMO diversity gain.

Step 8: The MCH of the receiving cluster acknowledges the data reception via an ACK packet. If such an ACK is not received, the CHs of the transmitting cluster retransmit their data (up to a given maximum number of retransmissions).

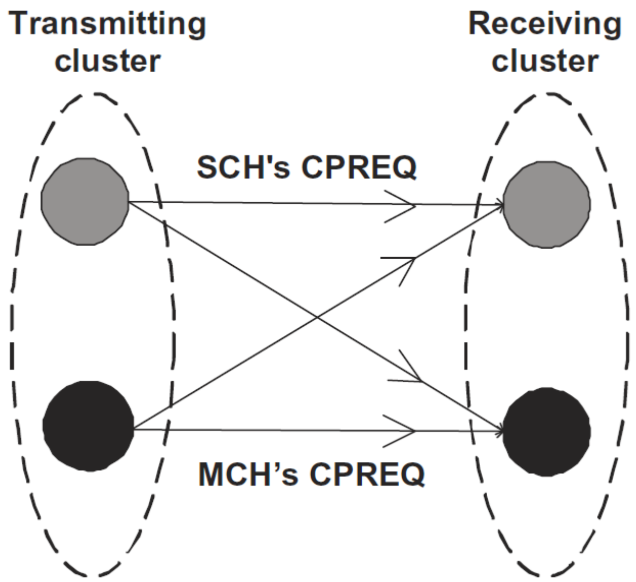

Fig. 4. Control packet exchanges between two clusters (MCHs are indicated by black circles and SCHs are indicated by gray circles).

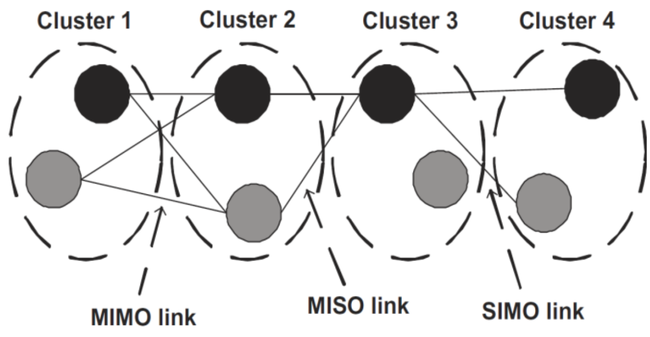

Fig. 5. Example of the WSN after step 5

3.3. Properties of CMIMO

CMIMO has several features. First, it is a distributed protocol because every node in the WSN independently makes its decisions based on local information. Second, at the end of the clustering process, a node is decided to be either a CH (master or slave) or a nonCH node. In other words, the clustering process is guaranteed to terminate. This can be easily proven by recalling that the node with the highest RBL in its neighborhood declares itself as an MCH. Such an MCH then selects an SCH according to one of the three criteria. Next, each nonCH node selects one of the MCHs to join. Third, an SCH cannot belong to more than one cluster. This is because an invited SCH responds to only one of the received requests from MCHs. Fourth, MCHs are evenly distributed because no two MCHs can be within each other's cluster range (as determined by the power level P_{intra}).

4. Energy Model

In this section, we analyze the energy consumption in the CMIMO protocol. The purpose of this analysis is to study the tradeoff between various parameters that are used in the system design, and also to obtain the energy values of the four possible transmission modes. Following [6], the total power consumed in sending a packet consists of transmission and circuit powers. The transmission power for intercluster data transmissions is adjustable and is given by $P_t = (1 + d)P_{out}$, where d is a factor that depends on the drain efficiency [29] of the power amplifier and the underlying modulation scheme [30], and P_{out} is the total transmit power at the air interface.

5. Design Issues

5.1. Connectivity

Before executing the CMIMO protocol, if the network of sensors is connected under a transmission range of R_{intra}, then after running the CMIMO protocol, the MCHs of any two neighboring nodes are either identical or are within range of $3R_{intra}$

5.2. Synchronization

One of the important design issues in operating CMIMO is synchronization. The importance of this aspect comes from the fact that synchronization allows CHs to fully exploit MIMO gains for intercluster communications. Extensive research has been done on quantifying the tradeoff between implementing synchronous network operation and the overhead and inaccuracy associated with such operation.

5.3. Reclustering

The key idea for reclustering is that when the RBL of any MCH falls below a specific threshold (e.g., 20% of its initial value), this MCH sends a ''reclustering'' message to its neighboring MCHs at power level P_{inter}. This message will be heard by the requesting MCH's nonCH nodes, its SCH, and its neighboring MCHs. Reclustering messages are similar to the ''hello'' messages used in the neighborhood discovery process in the clusterformation phase, except that they are sent at a higher power level (P_{inter}). Neighboring MCHs that hear a reclustering message relinquish their cluster head role and invoke a neighborhood discovery process. The rationale behind restricting the reclustering request to MCHs is that in most cases, MCHs are the ones that deplete their batteries first (before SCHs and nonCH nodes) because of their additional responsibilities in aggregating data, sending it to the SCH, and forwarding it to CHs in neighboring clusters. Reclustering may also be performed as a result of topological changes, but this aspect is not considered here because the network is assumed to be stationary.

5.4. Medium access control

We now discuss an issue related to the MAC layer, namely how to ensure reliable communications (i.e., taking packet losses into account). It should be emphasized that our work is mainly focused on the clustering/routing aspects of CMIMO, which take place at layers above the MAC layer.

6. Performance Evaluation

In this section, we evaluate the performance of CMIMO via simulations. We also compare it with the distributedclustering algorithm (DCA) [17], which resembles CMIMO in the criterion used to select CHs. The primary goal of this comparison is to demonstrate the benefits of cooperative MIMO over a single antenna system (represented by DCA). Recall that CMIMO adapts the transmission mode and power on a per packet basis. On the other hand, all transmissions in DCA take place using the SISO mode, where each cluster has only one CH.

We consider 100 stationary nodes that are randomly deployed in a square of length L_{max}. Unless stated otherwise, we take L_{max} = 1000 m, R_{intra} = 250 m, and R_{inter} = 750 m. Operating frequency is 2.5 GHz. In this case, the probability of finding two neighboring nodes whose distance is less than half wavelength is about 1.3 _ 10^{-4}. The sink is located to the right of the square, at a horizontal distance of 333 m and a vertical distance of 500 m from the bottom right corner of the field. Each node generates packets at rate k packets per second. The sink is the only node that is physically equipped with two antennas, enabling it to operate as a real multi antenna node. Multihop operation based on minimum energy routing is used for intercluster communications. The values of $c(M_t, M_r)$ that are required to achieve a target BER of 0.001 are taken from [6] to be: 24.4 dB for SISO, 10.6 dB for SIMO, 14.1 dB for MISO, and 6.9 dB for MIMO. For the wireless channel, we assume a Rayleigh fading model along with a distance dependent path loss, which has a power falloff of d^4. Other simulation parameters are given in Table 3. Our results are based on simulation experiments conducted using CSIM (a C based process oriented discrete event simulation package [32]). Each plot represents the average of 10 simulation runs.

6.1. Energy consumption

Fig 6 shows the impact of R_{inter} on the total energy consumption for CMIMO and DCA. In this experiment, SCH selection is done based on the amount of overlap between the neighbor lists of the MCH and SCH. The results illustrate that energy consumption increases with R_{inter}. CMIMO significantly outperforms DCA in energy consumption. The superiority of CMIMO over DCA becomes more apparent when R_{inter} is large. This is attributed to the fact that the higher the intercluster range, the higher the number of neighboring MCHs of a given MCH, and hence the higher the tendency to use multi antenna modes for inter-cluster communications (transmission energy dominates the circuit energy in this regime, making MIMO/ MISO/SIMO more energy efficient than the SISO mode).

Fig 7 depicts the energy consumption versus L_{max}. Because the number of nodes is kept constant 100 and, increasing L_{max} results in better energy performance for CMIMO compared with DCA. This is attributed to the fact that for large networks, the transmission energy dominates the circuit energy, forcing CMIMO to make more frequent use of MIMO/SIMO/MISO modes.

Table 1 Simulation parameters.

Data packet size	2000 bytes
Control packet size	20 bytes
${}^{P}DAC,{}^{P}ADC$	15 mW
${}^{P}mix$	30.3 mW
${}^{P}filt{}^{P}filr$	2.5 mW
${}^{P}syn$	50 mW
${}^{P}LNA$	20 mW
${}^{P}IFA$	2 mW

The impact of node density on the energy consumption is shown in Fig 8, which indicates that the total energy consumption increases with the number of nodes. It should be noted that CMIMO reduces the total energy consumption compared with DCA. This reduction becomes more noticeable under small number of nodes. The reason is that the distances between clusters become larger as the number of nodes decreases. In such a case, SISO becomes less preferable than other modes, which makes CMIMO more energy efficient than DCA.

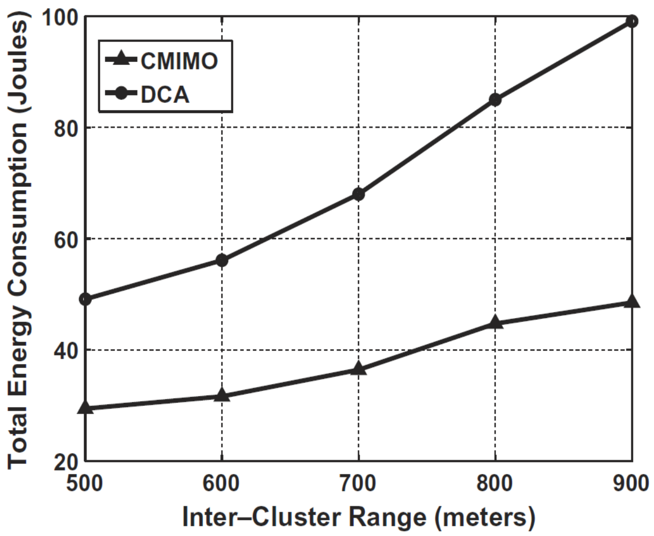

Fig. 6. Total energy consumption versus R_{inter}.

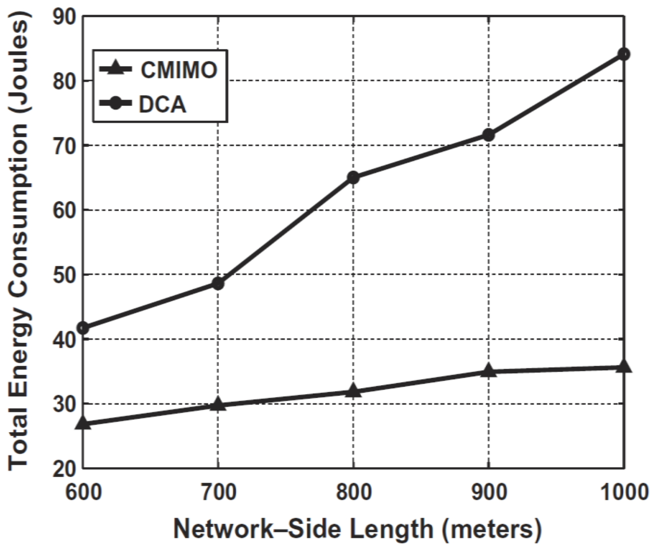

Fig..7. Total energy consumption versus network size

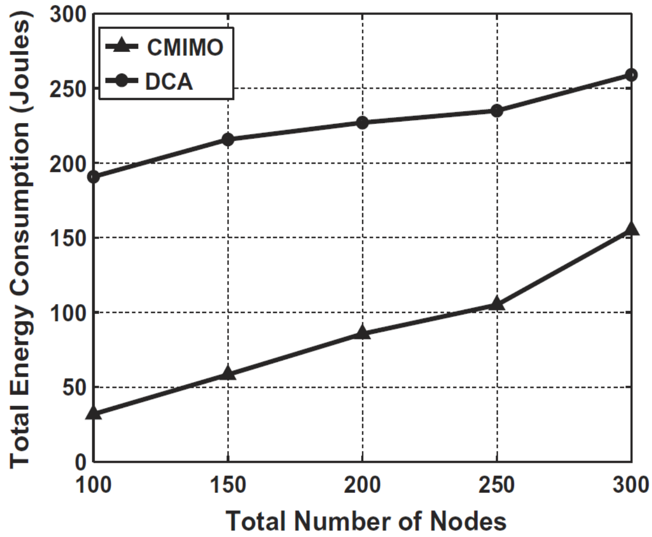

Fig. 8. Total energy consumption versus number of nodes

6.2. Transmission modes

Fig 9 depicts the percentage of time each transmission mode is used as a function of R_{inter}. For a single VMIMO link, it is known that when both transmission and circuit energies are account for, there exists a critical distance.

From the above figure 7 and 8 VMIMO communications is more energy efficient than SISO [6]. When $R_{inter} > D'$, RF transmission energy dominates the overall consumed energy, so using more cooperating antennas leads to lower overall energy consumption. In this regime, our CMIMO protocol favors the 2 _ 2 MIMO mode over other modes (see, for example, the case when R_{inter} = 900 m). On the other hand, when $R_{inter} < D'$, circuit energy is dominant, and the protocol favors SISO because of its lower circuit energy consumption. Note that R_{inter} is the average intercluster range. Variations around this average result in variations in the optimal mode for the same average value of R_{inter}.

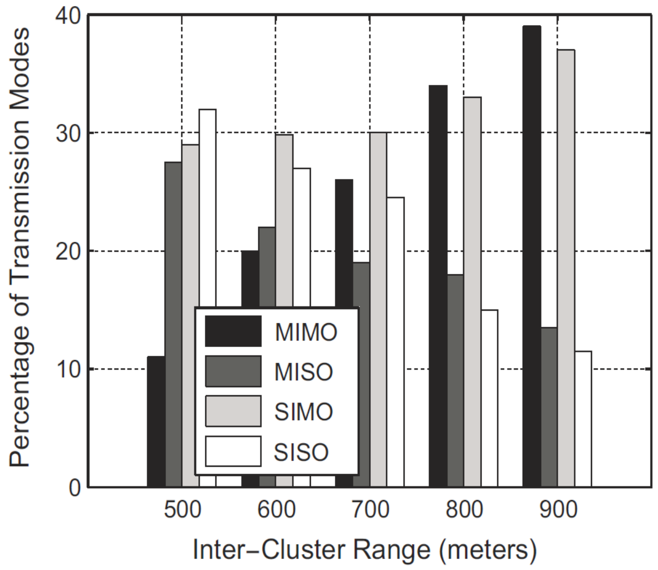

Fig. 9. Percentage of transmission modes versus intercluster range

6.3. Number of hops

We now study the impact of intercluster range and network area on the number of hops used for intercluster communications to the sink. The histogram of the number of hops needed for routing under different intercluster ranges.

As expected, under small intercluster ranges (e.g., 300 m), routes with large numbers of hops exist (10 hops). On the other hand, when the intercluster range becomes large (e.g., 900 m), fewer hops are needed (three hops).The figure reveals that large network areas require more hops between the communicating CHs and the sink. For example, a path with 15 hops exists when L_{max} = 1000 m. However, no more than eight hops are needed when L_{max} = 600.

7.Conclusion

We proposed a distributed and adaptive clustering/ routing protocol (CMIMO) to minimize the total energy consumption for a multihop WSN. CMIMO partitions a WSN into a number of clusters that have one or two CHs per cluster. In addition to routing and data aggregation/fusion functions, these CHs are also responsible for intercluster communications. The proposed CMIMO protocol has the ability to adapt the transmission mode (SISO, MISO,SIMO, MIMO) and transmission power on a perpacket basis for intercluster transmissions. We studied the performance of CMIMO via simulations. The results indicate that the proposed protocol achieves significant reduction in the overall energy consumption compared with non adaptive schemes that are designed with one CH per cluster and that use SISO (e.g., WSNs operated with the DCA scheme). Consequently, the network lifetime under CMIMO is significantly improved compared with SISObased protocols. The significance of CMIMO becomes more noticeable under large intercluster ranges and network sizes. We also derived the conditions on the inter and intra cluster communication ranges to guarantee network connectivity. These conditions are tighter than those previously reported in the literature, and are applicable to any clustering protocol.

Our work considered only MIMO’s diversity gain. An interesting future extension is to incorporate other MIMO gains in the same optimization framework, i.e., allow the protocol to dynamically switch between different types of MIMO gains (and antenna modes), depending on both energy consumption and throughput considerations.

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