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Energy Efficient Virtual MIMO Communication for Wireless Sensor Networks

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Abstract Virtual multiple input multiple output (MIMO) techniques are used for energy efficient communication in wireless sensor networks. We investigate virtual MIMO for fixed and variable rates. We propose energy efficient routing based on virtual MIMO. The simulation results show that virtual MIMO based routing is more energy efficient as compared to SISO (single input single output) for larger distances.

1 Introduction

In recent years, virtual MIMO has attracted a growing interest because of its energy efficiency in large field of networks. In virtual MIMO network, a group of sensors cooperate to transmit and receive data. Although the participation of multiple transmitters and receivers in a transmission save significant energy in long-range communications, the increase in the number of transmitters and receivers also increases the circuitry power consumption. As a result, the energy optimization techniques have to be adapted with the environment. Due to the circuitry complexity and difficulty of integrating

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separate antenna, virtual MIMO concepts are applied in wireless sensor networks (WSNs) for energy efficient communication to save energy and increase reliability.

A large number of protocols and methods are proposed for energy efficient communications in WSNs. In this paper, we would like to investigate cooperative virtual MIMO that provides energy efficient communication by sharing the transmission and reception of information. In virtual MIMO, multiple senders and receivers participate in long-range communication to improve data reliability in fading channels. The performance of virtual MIMO in WSNs depends on the structure of network layer and data link layer. There are several approaches for implementing virtual antenna array in WSNs. Although the core implementation of virtual antenna array or co-operative transmission lies on physical layer, there is deep dependency on the higher layers (network and data link) to implement this issue. In a cognitive network framework, the network components can modify the operational parameters to respond to the needs of particular environment. We propose a cluster based virtual MIMO cognitive model with the aim of changing operational parameters (constellation size) to meet the optimum design.

The remainder of the paper is organized as follows. Section 2 describes the related work. Section 3 describes the proposed network architecture and the total energy consumption of the proposed architecture. Section 4 describes the simulation and results. Finally, Section 5 concludes the paper and provides directions for future work.

2 Related Work

Initially, in Cui et al. (2004), the authors propose MIMO for WSNs, where MIMO is based on Alamouti diversity schemes and it is extended to individual single antenna array nodes. The array nodes cooperate with each other to form multiple antenna transmitters or receivers. By receiving and sending information jointly, a lot of energy can be saved. MIMO system outperforms SISO (Single Input Single Output) after a certain distance. By maintaining the proper constellation (bits per symbol) size, MIMO can outperform SISO in case of long haul distance. The authors extended the idea to implement virtual MIMO where each antenna on the transmitter side is used as the antenna array for MIMO communication. In Cui et al. (2005), the authors incorporate multiple layers for co-operative transmission. By designing routing and link scheduling in upper layers, MIMO can reduce energy consumption with improving end-to-end performance. In this work, long haul communication for base station is investigated by 2x2 MIMO without any local information exchange.

In del Coso et al. (2006), the optimum time management and power budget allocation for virtual MIMO is proposed. Their analysis shows that virtual MIMO works like actual MIMO for low signal to noise ratio. The results show that the energy saving is increased with the increase of hops.

According to Chen et al. (2005b), the optimized number of nodes in a cluster and optimized number of hops save energy for virtual MIMO communication. Training overhead and orthogonal STBC have been investigated in their MIMO architecture to support channel estimation and multiple antennas. In their analysis, the same group of nodes are used as transmitters and receivers for relay, which causes the early death of network.

In Jayaweera (2004), the authors include the training symbols for fading channels and their analytical results show that the energy consumption of MIMO is lower as compared to SISO. In Jayaweera (2005), data gathering nodes are considered without any energy constraint and multiple antennas are integrated on these nodes. Channel path loss and periodic symbols for channel estimation are incorporated to estimate total energy consumption. In Jayaweera (2006), the energy consumption is considered for 2x2 MIMO for the extra overhead symbols for multiple transmitter and receiver antennas. Although more training overhead is needed for multiple transmitters, the analytical model shows that the energy consumption is low as compared to SISO, when transmission distance, transmission rate, and time period are carefully maintained. In Jayaweera, the receiver nodes cooperate instead of transmitter nodes; the transmission time should be adaptive to achieve lower energy consumption as compared to SISO.

In Yuan and He (2006a), a cross layer architecture is proposed, where multiple senders transmit data to single receiver of the nearby cluster. The selection of appropriate set of transmitters can save significant energy for MIMO. In Yuan and He (2006b), the authors consider both the inter cluster and intra cluster communication energy to select the appropriate co-operative transmitter nodes. In the energy consumption model, AGWN and Rayleigh Fading channels have been considered for intra-cluster and inter-cluster communication respectively.

In Zhang and Dai (2007), space-time block coding and spatial multiplexing code on optimal transmission strategy is described. The scheme can reduce the critical distance for virtual MIMO. The authors have also investigated the switching parameters of coding system for energy saving high rate data transmission in MIMO.

In Chen et al. (2005a), the energy consumption for virtual MIMO communication in multi hop network is analyzed. The proposed protocol selects the nodes and provides the routing path for efficient MIMO communication. Different MIMO combinations are considered for full cooperative and half cooperative transmissions in Liu and Xiaohua Li (2005). In Qing-hua et al. (2007a), cooperative nodes are selected for MIMO communication. Fixed rate data are considered for communication between clusters. The energy model justifies the efficiency of virtual MIMO communication for sparse sensor network.

In the above proposals, multiple nodes are not considered for both transmitters and receivers in multi-hop communication. This limits the full advantage of energy saving for virtual MIMO. In this paper, we study the feasibility of integrating multiple transmitters and multiple receivers for cluster to cluster communication in multi hop WSNs. Again, we determine the routing path based on the virtual MIMO communication cost to delay the first node death , which is first time proposed system in this paper according to our knowledge.

3 Cognitive Network Framework

In usual WSNs, in one transmission, there is one transmitter and one receiver; in other words, the transmission is SISO, single input single output. However, it is possible to use multiple transmitters and multiple receivers in one transmission.

Figure 1 shows the scenario of using three transmitters and two receivers. The sender node, S, transmits a message to the destination node, D. First, S transmits the message to three transmitter nodes, t_1, t_2, and t_3. These transmitter nodes transmit the message to the receiver nodes, r_1 and r_2. Then, the receiver nodes forward the message to the destination node, D.

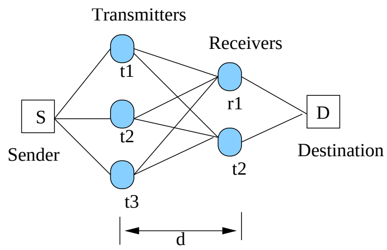


Fig. 1 Virtual MIMO Example

In MIMO, the multiple transmitters and receivers provide energy efficient long haul transmissions, Cui et al. (2004). We use virtual MIMO in WSNs as compared to MIMO because we cannot integrate multiple antennas in small sensors due to space limitations and circuit complexity. We assume, our network is synchronized with the message from control channel Cui et al. (2006), Zhang and Dai (2007), Qing-hua et al. (2007b). For MIMO communication, we use STBC coding for diversity with a trade off between diversity and multiplexing Zheng and Tse (2003).

Based on the number of transmitters and receivers, we may get the following combinations: MIMO (multiple input multiple output), SIMO (single input multiple output), MISO (multiple input single output), and SISO (single input single output). Further, depending on the transmission distance, data rate, and number of transmitters and receivers, the appropriate mode of transmission, MIMO, SIMO, MISO, or SISO would be determined.

The transmitters' bit rate, b is defined as bits per symbol. Further, as constellation size is defined as the number of bits modulated per symbol, the constellation size is equal to the transmitters' bit rate, b. Moreover, for MIMO and variable rate techniques, the constellation size depends on the distance d between the transmitters and receivers; as a result each link will have its own data transmission rate. However, for fixed rate systems, constellation size does not vary with the distance d, Cui et al. (2004).

The constellation size can be adjusted in the data link layer for each route where the routing path is established in network layer Cui et al. (2006). The cooperation of both layer optimizes the energy savings for virtual MIMO communication.

As MQAM is a variable data rate modulation scheme, constellation size b can be defined as $b = log_2 M$. Further, we can define constellation size in terms of number of bits L, Bandwidth B, and duration radio transceiver is on T_{on}, and data rate R_b, Cui et al. (2005). .

$$b = \frac{L}{BT_{on}} = \frac{R_b}{B} \quad (1)$$

where data rate (bits/second), $R_b = L/T_{on}$.

In WSNs, the sensor node has a low duty cycle and the node is off for most of the times in order to conserve energy. The energy consumption is computed by adding the on, sleep, and transient states, as given below.

$$E = P_{on} \times T_{on} + P_{sleep} \times T_{sleep} + P_{transient} \times T_{transient} \quad (2)$$

where, P_{on}, P_{sleep}, and $P_{transient}$ represents power on, sleep and transient respectively. Similarly, T_{on}, T_{sleep}, and $T_{transient}$ are duration for on, sleep and transient states respectively. For simplicity, sleep time is ignored, Cui et al. (2004).

$$P_{on} = P_{transmission} + P_{circuit} \quad (3)$$

Transmission power $P_{transmission}$ includes two components: power to transmit $P_{trasnmit}$ and amplifying power, $P_{amplifying}$.

$$P_{transmission} = P_{transmit} + P_{amplifying} \quad (4)$$

Further, $P_{amplifying}$ is a factor of transmit power, $P_{amplifying} = \alpha P_{transmit}$, $P_{transient} \approx 2P_{syn}$, where P_{syn} is power consumption for frequency synthesizer, Cui et al. (2005). Equation 2 can be described as follows:

$$E = [P_{transmit}(1 + \alpha) + P_{circuit}] \times T_{on} + 2P_{syn} \times T_{transient} \quad (5)$$

As the power consumption in $T_{transient}$ is negligible as compared to $P_{circuit}$, the constant factor P_C is used to represent both circuitry consumption and synthesizer consumptions.

$$E = [P_{transmit}(1 + \alpha) + P_C] \times T_{on} \quad (6)$$

We refine the results presented in Cui et al. (2004). Transmit power is obtained by the following equation:

$$P_{transmit} = \bar{E}_b R_b \times \frac{(4\pi)^2 {d_{ij}}^{k_{ij}}}{G_t G_r \lambda^2} M_l N_f \quad (7)$$

where $\bar{E}_b$ is the required energy per bit for receiver, R_b is bit rate, G_t is transmitter antenna gain, G_r is receiver antenna gain, d_{ij} is distance between nodes i and j, k_{ij} is the path loss factor from node i to j, λ is wavelength, M_l is the link margin, and N_f is the receiver noise.

As transmitter has to distribute the power among all the receivers, Equation 6 can be refined as follows from Cui et al. (2004):

$$E_a = \frac{2}{3}(1+\alpha)(\frac{P_b}{4})^{-\frac{1}{N_T N_R}} \frac{2^b - 1}{b^{\frac{1}{N_T N_R}+1}} N_0 \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} \frac{(4\pi)^2 {d_{ij}}^{k_{ij}}}{G_t G_r \lambda^2} M_l N_f + \frac{P_C}{R_b} \quad (8)$$

where $\alpha = \frac{\xi}{\eta} - 1$ is an amplifying factor, E_a is average energy consumption per bit, N_T and N_R are number of transmitters and receivers respectively, $\bar{P}_b$ is the average bit error rate, N_0 is single sided noise power spectral density and total circuit power consumption $P_C = N_T \times P_{ct} + N_R \times P_{cr}$.

The invariant variables of Equation 8 are given as follows:

$$\zeta = \frac{2}{3}(1+\alpha)(\frac{P_b}{4})^{-\frac{1}{N_T N_R}} \frac{2^b - 1}{b^{\frac{1}{N_T N_R}+1}} N_0 \frac{(4\pi)^2}{G_t G_r \lambda^2} M_l N_f \quad (9)$$

Using Equation 1, Equation 8, and Equation 9, we obtain the following:

$$E_a = \zeta \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} {d_{ij}}^{k_{ij}} + \frac{P_C}{bB} \quad (10)$$

Cui et al. (2004) use same path loss factors for multiple transmitters and receivers; however, in our approach, Equation 10, we consider different path loss factors for all transmitters and receivers. As a result, transmit power could be different for each path loss factor. He and Wu (2007) consider multiple transmitters for communication with different path loss factors with fixed rate system. However, we consider both multiple transmitters and receivers with individual path loss factors for variable rate systems.

From Equation 10, E_a can be minimized as follows:

1. increase b, constellation size
2. decrease d_{ij}, distance between transmitter and receiver

Further, it is assumed that when d_{ij} is decreased, the path loss is also decreased or at least remain constant. The appropriate choice of transmitters and receivers in cluster can significantly vary the distance d_{ij}. However, the constellation size, b, can not be significantly increased as it is linearly dependent on the transmission energy, Cui et al. (2006); Jayaweera (2006). The constellation size can be identified for the particular distance. As this problem is non-convex integer problem, Cui et al. (2004, 2005), an optimal constellation size b can be determined by an iterative method as given in He and Wu (2007).

3.1 Virtual MIMO nodes Selection

In a cluster, some nodes are selected as transmitter nodes and some nodes are selected as receiver nodes. Same node can be selected as both transmitter and receiver. To minimize the distance between transmitters and receivers, the cluster-head (CH) selects the appropriate set of transmitter and receiver nodes.

In the proposed virtual MIMO framework, there are four types of nodes: normal nodes, transmitter nodes, receiver nodes, and cluster heads. The normal nodes sense and collect data regarding the environment. The Cluster head (CHs) collect data from the normal nodes and use transmitter nodes to transmit their data to the receiver nodes of the neighboring cluster or send data directly to the base station. All the nodes in the cluster will transmit data to the CH using CSMA-CA slotted algorithm IEE (2006). CH will aggregate the packets into a single packet and will broadcast to the transmitter nodes.

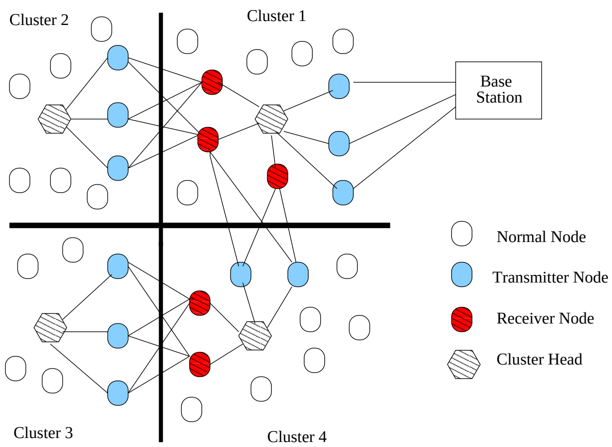


Fig. 2 Virtual MIMO Network

Figure 2 shows four clusters with different transmitter and receiver nodes. For instance, Cluster 1 has three transmitter nodes that directly communicate with the base station. Cluster 2 has three transmitter nodes that communicate with 2 receiver nodes of Cluster 1. In other words, there is multi-hop communication from cluster 2 to cluster 1 and then from cluster 1 to base station. Similarly, the two transmitter nodes of Cluster 4 communicate with 2 receiver nodes of Cluster 1. It should be noted that the same receiver node of Cluster 1 is used by transmitters of both clusters 2 and 4. In other words, it is possible, that a receiver node is used by multiple transmitter nodes. Cluster 3 has two options to reach to the base station: a) Cluster 2, and b) Cluster 4. However, Cluster 4 is selected because of reduced energy consumption as compared to Cluster 2, in terms of MIMO communication.

The cluster heads (CHs) are selected based on their available energy and current load requirements. In our scenario, nodes with highest energy are selected as CHs. The CHs broadcast their advertisements and the other nodes will choose their cluster heads based on the received signal strength of the advertisement messages. Then, a spanning tree based routing algorithm is used to determine the routing path between CHs.

Figure 3 shows the pseudo-code of the routing algorithm that gives the transmitters and receivers based on MIMO communication. At the beginning, *List* contains all the CHs. First, the CH with the minimum energy, CH_{min}, is obtained from the *List*. Then, the most energy efficient MIMO combination of transmitters and receivers is obtained for this CH_{min}; where, the criteria of selection is based on the constellation size that gives the minimum energy consumption, using our proposed virtual MIMO network, i.e., Equation 10.

The set of transmitters are associated with the CH_{min} as shown by the operation $CH_{min}(T)$. Similarly, the receivers are associated with the CH_{min} by the operation $CH_{min}(R)$. Further, it should be noted that the transmitters $(t_1 \dots t_n)$ are the set of nodes of this cluster and the receivers $(r_1 \dots r_m)$ are the set of nodes of a neighboring cluster (the next hop). Then, the above process is repeated for all the CHs in the *List*. Section 3.2 describes the selection process of transmitters and receivers.

procedure $MIMO - RoutingPath(List)$
/* $List$ contains all the cluster heads */
while $List \neq \phi$ do
  $CH_{min} \longleftarrow ExtractMin(List)$
  $EstimateMIMOEnergy(CH_{min})$
  $CH_{min}(T) \longleftarrow \{t_1 \dots t_n\}$
  $CH_{min}(R) \longleftarrow \{r_1 \dots r_m\}$
end while

Fig. 3 MIMO Routing Path

Further, it is also possible that the cardinality of the set of transmitters is 1. In that case, it would be SIMO. Similarly, it is possible, that the number of receivers would be 1, MISO. Finally, we may have cardinality of 1 for both transmitters and receivers, in that case it would be SISO. In other words, the outcome of the $EstimateMIMOEnergy()$ technique could be anyone of the following: MIMO, MISO, SIMO, or SISO, based on the distance, communication cost, constellation size, data rate, path loss, and other parameters. The transmitter nodes adapt to the constellation size in the link layer, Cui et al. (2005). The transmitter nodes forward the data packets based on the optimized constellation size using space-time block code, Tarokh et al. (1998). The transceivers use the MQAM as the modulation technique to support higher data rate. The receiver nodes receive the packets from all senders and transfer the block codes to the CH using uncoded MQAM. Alamouti code can be used as space-time block code for two transmitters and two receivers, Jayaweera (2006); Yuan and He (2006a); Alamouti (1998). The CH forwards the packet to the sender nodes of the neighboring CH or to the base station.

3.2 Selection of Transmitters and Receivers

We investigate three different techniques for selection of transmitters and receivers: a) random selection, b) CH shortest method, and c) near optimum selection. In *random selection*, the transmitters and receivers are chosen randomly. In *CH shortest method*, the nearest transmitters and receivers from cluster heads are selected. The details of *near optimum selection* technique are as follows:

1. For each potential transmitter, the transmitter CH will determine receivers that are nearest to these transmitters.
2. The transmitter-receiver pairs are sorted based on distance.
3. The cluster head will choose the required number of transmitters and receivers from the sorted list.
4. If the number of transmitters or receivers are less than the required number of transmitters or receivers, the nodes nearest to selected transmitters and receivers are selected.

For instance, consider a transmitter CH containing four potential transmitter nodes, t_1, t_2, t_3, and t_4 and receiver CH containing four potential receiver nodes r_1, r_2, r_3, and r_4. Consider a case where we have to select 2 transmitters and 3 receivers. First, the transmitter-receiver pairs are selected: $t_1 - r_2 = 11$, $t_2 - r_1 = 10$, $t_3 - r_1 = 15$, and $t_4 - r_1 = 12$. Then, the list of pairs is sorted, $t_2 - r_1 = 10$, $t_1 - r_2 = 11$, $t_4 - r_1 = 12$, and $t_3 - r_1 = 15$. As only two transmitters are needed, $t_2 - r_1 = 10$ and $t_1 - r_2 = 11$ are selected; transmitters are t_1 and t_2 and receivers are r_1 and r_2. As the required number of receivers is 3, we need one more receiver. The third receiver is selected from the receivers that are nearest to r_1 and r_2. If the nearest neighbor from r_1 is r_3, r_3 will be selected as the third receiver. Since we have obtained the required number of receivers, there is no need to consider another nearest neighbor from r_2.

3.3 Energy Consumption Analysis

We assume the power consumption of each bit for transmission, transmitter circuit and receiver circuit is P_{intra}, P_{ct} and P_{cr} respectively. All the nodes in a particular data gathering period send data to local cluster head. Energy consumption for baseband signal processing is negligible compare to the total energy consumption and omitted in this section. Assuming the same packet size (N_B bits) , the energy consumption to transmit T packets from T nodes can be described by Eqn. 11

$$\rho = \frac{TN_B}{bB}(P_{intra} + P_{ct} + P_{cr}) \tag{11}$$

Cluster head will aggregate the packets and send the aggregated packet to all the transmitter (N_t) nodes. The energy consumption to transfer the packets to transmitter nodes can be described by Eqn. 12

$$\sigma = \frac{N_B}{bB}(P_{intra} + P_{ct}) + \frac{N_B N_T P_{cr}}{bB} \tag{12}$$

In long haul communication, transmitter nodes communicate with the possible shortest distance nodes of the receiver cluster by optimum constellation size. The energy consumption for cluster to cluster communication can be stated from Eqn.10

$$\tau = N_B C \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} {d_{ij(optimized)}}^{k_{ij}} + \frac{N_B P_C}{b_{(optimized)} B} \tag{13}$$

We assume n training bits are transmitted for channel estimation for each diversity. According to Jayaweera (2004) Eqn 13 can be described as

$$\tau = (nN_T N_R + N_B) C \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} {d_{ij(optimized)}}^{k_{ij}} + \frac{N_B P_C}{b_{(optimized)} B} \tag{14}$$

The transmission from receiver nodes to Cluster Head is local communication and can be assumed by Eqn 15.

$$\omega = \frac{N_R N_B}{bB} (P_{intra} + P_{ct} + P_{cr}) \tag{15}$$

The energy consumption from the last hop's transmitter nodes to base station is a special condition of Eqn. 14 where M_r =1.

Total energy consumption model can be described as following:

$$\rho + (Number\ of\ hops + 1) \times \sigma + (Number\ of\ hops + 1) \times \tau + \omega \times (number\ of\ hops) \tag{16}$$

4 Simulation

The proposed virtual MIMO network is simulated using the model described in Equation 10. The simulation details are as follows: number of nodes is 50, network area is 100m × 100m, base station is located at the center of the network and also moved in the horizontal direction to observe the effect of distance from the base station. The simulation is repeated for 10 experiments using 10 arbitrary seeds. The development environment is JDK 1.6 (Eclipse SDK). The simulation parameters are given in Figure 4.

We compare the energy consumption of MIMO, MISO, SIMO, and SISO. Figure 5 shows the graphs of energy consumption with respect to the distance from the base station. Initially, the base station is placed at the center of the network. Then, the base station is moved away from the center in the horizontal direction. As the network dimensions are 100m × 100m, the initial location of base station is 50m. As shown in Figure 5, the energy consumption in SISO is higher than all the other cases. Further, for most of the cases, the standard deviation of SISO is also higher as compared to the other techniques. As there is no cooperative nature in SISO and all the decisions are independent of the other resources, the high standard deviation in energy consumption values is not unexpected. MIMO performs better than SIMO for most of the cases until the cross over point at 120m, where the large distance of base station becomes the dominant factor. In this example, MISO

B	10000
η	0.35
N_f	10 dB
σ^2	-174 dBm/Hz
K	2∼5
$G_t G_r$	5
P_b	10^{-3}
f_c	2.5 GHz
N_0	-171 dBm/Hz
λ	0.12m
M_l	40 dB
N_f	10 dB
P_{ct}	0.0844263 W
P_{cr}	0.112497827 W
ξ	$3\frac{\sqrt{M}-1}{\sqrt{M}+1}, M = 2^b$

Fig. 4 Simulation parameters.

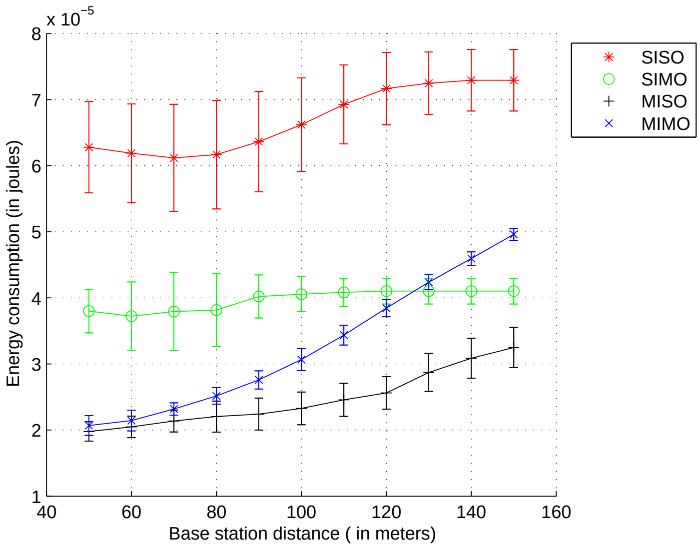


Fig. 5 Energy Consumption for MIMO, MISO, SIMO, SISO networks

has performed better than MIMO for all the cases because if base station is in direct range, it is more energy efficient to send the packets directly as compared to another set of transmitters.

Figure 6 shows the energy consumption of virtual MIMO for fixed and variable rates. The constellation size is adapted to minimize the energy consumption. As expected, the energy consumption is not increased linearly as the base station is moved away from the center. The increase in energy consumption for fixed rate is almost linear with respect to the increase in the distance of the base station. However, for the variable rate, the increase in

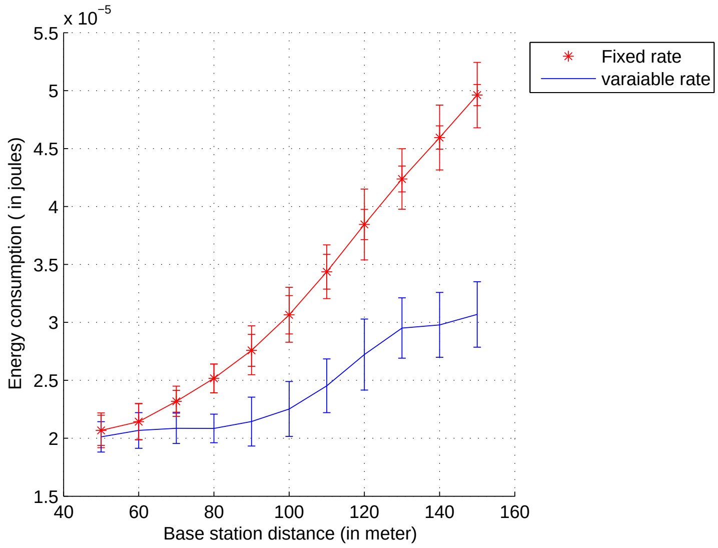


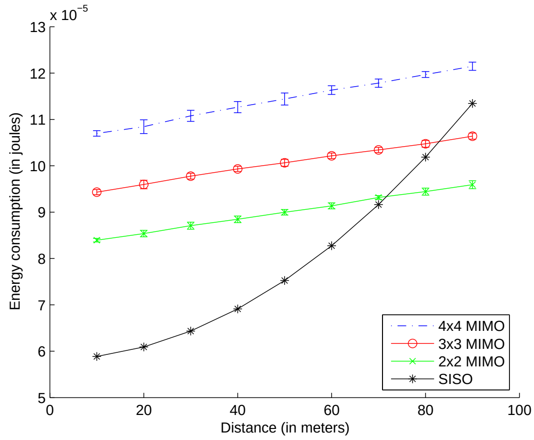
Fig. 6 Energy Consumption of Virtual MIMO for Fixed and Variable Rates

energy consumption is not directly proportional to the distance of the base station and the algorithm becomes more effective as the distance is increased.

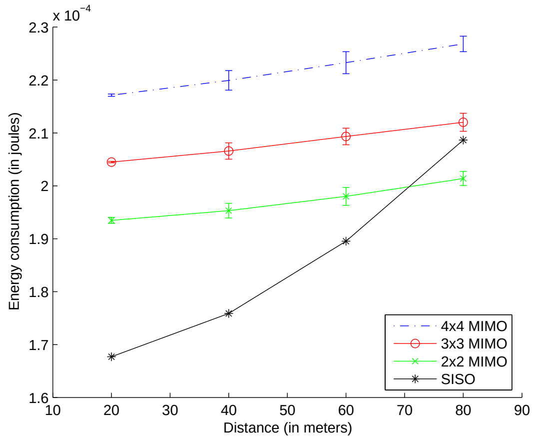
Figure 7 shows graphs of total energy consumption of SISO and various virtual MIMO techniques such as 4x4, 3x3, and 2x2. Figure 7(a) and Figure 7(b) show the results when the distance between clusters is 10m and 20m respectively. The transmission cost from one cluster to another cluster includes local transmission cost and long haul transmission cost from one cluster to another cluster. The results show that SISO performs better than MIMO techniques for smaller distances; however, at larger distances, greater than 75m, MIMO (2x2) has lower energy consumption as compared to SISO. Further, MIMO with 2x2 (2 transmitters and 2 receivers) is more efficient than all other MIMO combinations, e.g. 3x3 MIMO and 4x4 MIMO. Figure 7(a) and Figure 7(b) show that similar performance is observed when the distance between clusters is increased from 10m to 20m, although there is significant increase in overall energy consumption, which is expected because of increase in transmission range.

Figure 8 shows graphs of energy consumption for long-haul communication for SISO and various MIMO techniques. In this scenario, the local transmission costs within a cluster are not incorporated. The results show that if only long-haul communications are considered, MIMO combinations perform better than SISO for all transmission ranges.

Figure 9 shows graphs of energy consumption for three different transmitter-receiver selection techniques: random selection, near optimum selection, and CH shortest. The results are obtained for three MIMO configurations: 2x2 MIMO, 3x3 MIMO, and 4x4 MIMO. The results show that near optimum selection technique is better than other techniques for all cases. Although



(a) 10m distance between clusters



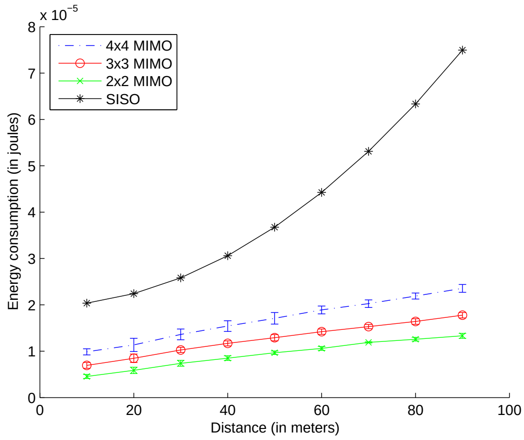
(b) 20m distance between clusters

Fig. 7 Total energy consumption of various virtual MIMO and SISO

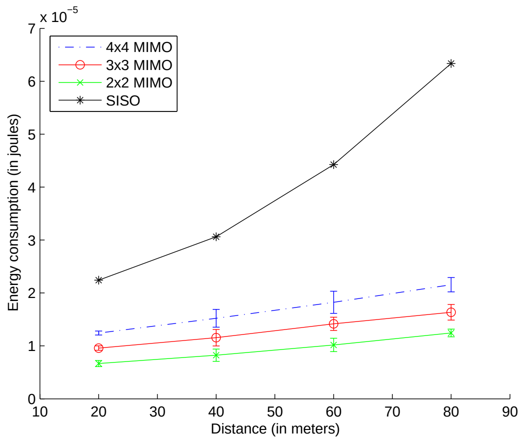
near optimum selection technique is not computation intensive, it provides better selection of transmitters and receiver nodes.

Figure 10 shows bar charts for constellation sizes using different transmitter and receiver selection strategies, for three different MIMO configurations 2x2, 3x3, and 4x4. The distance between cluster to cluster is fixed as 10m.

Figure 11 shows the graphs of percentage alive nodes with respect to the number of rounds. A round is completed when the CH receives all the data from its current members. The distance between two clusters is 80m. The results show that 2x2 MIMO performs better than other techniques. As the transmitters and receivers are not changed dynamically, they are used until their energy is depleted. As a result, the number of nodes die in batches,



(a) 10m distance between clusters

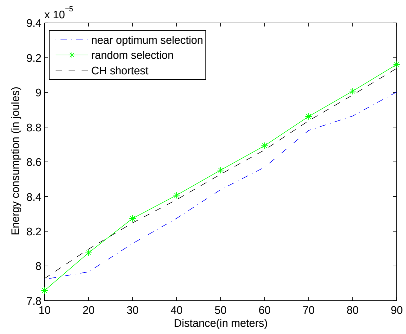


(b) 20m distance between clusters

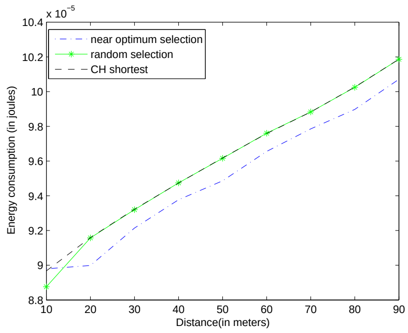
Fig. 8 Energy consumption of only long-haul communication for various virtual MIMO communications

which is shown by piece-wise linear graphs. In other words, the transmitters and receivers die around same time and then, a new set of transmitters and receivers are selected.

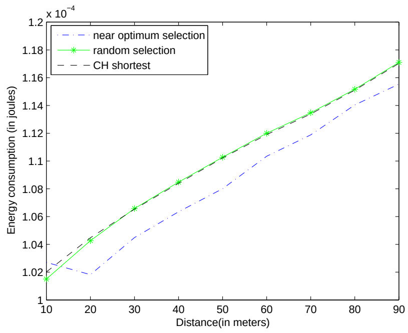
Table 1 shows comparison of first node death for different techniques. MIMO techniques perform better than SISO, SIMO, and MISO techniques in delaying the first node death. However, there is very little variation in 2x2 MIMO, 3x3 MIMO, and 4x4 MIMO techniques in terms of delaying the first node death.



(a) 2x2 MIMO



(b) 3x3 MIMO

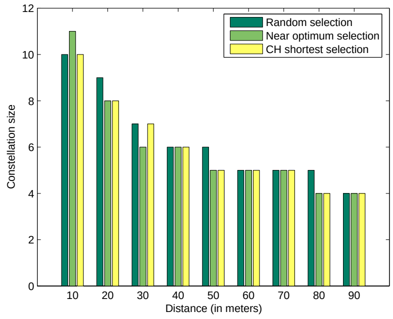


(c) 4x4 MIMO

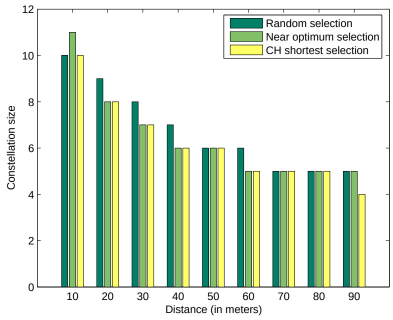
Fig. 9 Different selection of transmitters and receivers

5 Conclusion

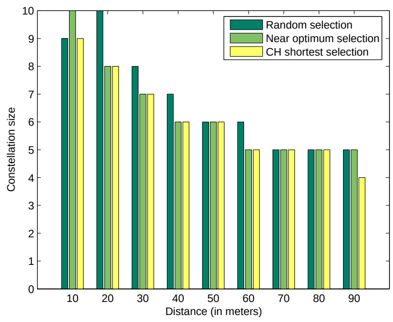
For energy efficient communication in WSNs, we investigate the use of multiple transmitters and multiple receivers in virtual MIMO. We consider the cases for fixed rate as well as variable rate constellations. Further, we investigate the impact of distance and long range distance on the choice of MIMO,



(a) 2x2 MIMO



(b) 3x3 MIMO



(c) 4x4 MIMO

Fig. 10 Constellation size for different selection of transmitters and receivers

MISO, SIMO, and SISO. We assume that the transmitters and receivers for each cluster are selected in offline and then the optimized constellation size is adapted for the cluster. In future, the proposed framework can be extended for the dynamic clusters, where the constellation size is determined in online process. Further, we would like to investigate the cluster formation, network density, network area, and the impact of different routing strategies.

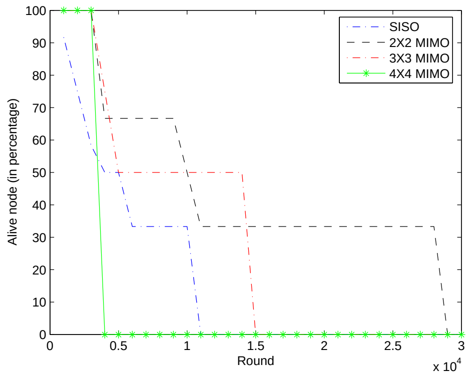


Fig. 11 Network lifetime for SISO,SIMO,MISO,MIMO

Communication Type	First node death round
SISO	572
SIMO	2866
MISO	583
2X2 MIMO	3423
3X3 MIMO	3446
4X4 MIMO	3462

Table 1 First node death for different communication techniques

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