

# COMBINED IEEE 802.15.4 PHYSICAL LAYER AND VIRTUAL MULTIPLE INPUT MULTIPLE OUTPUT (V-MIMO) TRANSMISSIONS FOR ENERGY EFFICIENT WIRELESS SENSOR NETWORKS

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## ABSTRACT

*A Wireless Sensor Network (WSN) consists of a hundred of sensor nodes deployed in sensing fields in order to serve various applications. The limited resources of sensor nodes such as energy source, computational ability and communication bandwidth are the most important challenges in designing a reliable smart WSN which guarantees the connectivity and maximizes the lifetime of sensor's batteries. One of the available solutions for improving the energy efficiency of smart WSNs is by using the Virtual Multiple Input Multiple Output (V-MIMO) technology adapted to sensor nodes. In this paper, we proposed a high energy efficiency smart WSN in which we exploited the advantages Provided by the virtual MIMO technique (i.e. by reducing the multipath fading channel). Our network transmission has two scenarios. The first scenario is based on deploying one rechargeable relay node at the center of the sensing field which is responsible for receiving data packets from the source node, decoding and forwarding them to a destination node, while the second scenario is based on dividing the sensing field into clusters where each cluster has a rechargeable relay node which transfers data packets to a destination node in the same cluster or in any other cluster. In this work, we studied the effects of Rayleigh flat fading channels which increase the re- transmission error of data packets. Our simulation results show that the use of the advantages of virtual MIMO and one central/rechargeable relay node achieves only low energy efficiency for the Signal to Noise Ratio (SNR) range between  $-20$  to  $20$ dB over the Rayleigh flat fading channel. However, the second scenario achieves high energy efficiency due to the clustering technique and the central relay nodes with direct transmission in each cluster.*

## KEYWORDS

*Smart wireless sensor networks, high energy efficiency WSNs, virtual MIMO*

## 1. INTRODUCTION

A Wireless Sensor Network (WSN) is composed of a large number of sensor nodes and some sink nodes which are interconnected wirelessly with each other. WSNs are characterized by low power and lossy networks as all sensor nodes have limited power resources and operate in harsh environments [1]. If a sensor node is located far from the sink node, i.e. not within the direct communication range of a sender, then the transmission occurs in a multi-hop manner. In this scenario, data packets need to be transmitted from one sensor to another all the way until the packets reach the destination node. Thus, hotspot nodes that are located closer to the sink node, deplete energy faster due to the fact that their transceiver needs to be turned ON most of the time. As a result, the lifetime of WSNs will decrease [2].

One solution to solve the problem of the multi-hop transmission is to divide the sensing field into clusters. These clusters consist of many sensors which form a group of nodes for

achieving efficient power consumption in WSNs. Each cluster will have a nominated cluster head which is the node that is responsible for collecting data packets from sensor nodes inside the cluster and forwarding them to a sink node for further communication. In general clustering techniques have been discussed extensively in the literature either as a standalone protocol [3] or as the side effect of other techniques such as the routing protocol [4] or the topology control technique [5]. The majority of clustering protocols and techniques lead to power efficient design of WSNs because sensor nodes send data packets over shorter distances to their nominated cluster head [6]. However, when sensor nodes inside a cluster follow 1-hop transmission scenario, i.e. the data packet will be transferred from sensor nodes which are located no more than 1 hop away from a cluster head, and nodes deployed in a large sensing field where many sensor nodes are installed to perform their functions, many clusters will be generated and hence many cluster heads will be nominated. Thus, the same problem will occur as if there are no clusters [6].

Another solution to have power efficient design of WSNs for a large sensing field is by using the multiple antenna communication technique (or Multiple-Input-Multiple-Output (MIMO)). This technique has gained a significant attention in recent years. However, the noticeable drawbacks of MIMO are increasing complexity of transceiver circuitry and the power consumption due to the necessity to perform large amounts of signal processing [7]. These drawbacks contradict the fact that WSNs have limited power resources. In addition, the small size of sensor nodes increases the difficulty in adapting the MIMO technique for WSNs, and which becomes unrealistic. Therefore, in order to apply the MIMO technique for WSNs we need to consider the circuit power consumption and the transmit power consumption. Authors in [8] have discussed the possibility of implementing the MIMO technique in WSNs even though sensor nodes consumed additional circuit power or communications overhead. However this can be achieved via cooperative communications techniques such as Virtual MIMO (V-MIMO) [7][8].

The present work shows how the V-MIMO technique can be adapted to provide significant energy efficiency for WSNs by using judicious selection of system parameters and transmission scenarios at the design level. Particularly, the main contributions of this work is threefold:

1. Implementation of the Zigbee physical layer using IEEE 802.15.4 specifications which requires long battery life of a sensor node.
2. Application of two proposed transmission scenarios either by dividing the sensing field into clusters or by using direct transmission to the next sensor node in the transmission path until data packets reach their destination.
3. Implementation of V-MIMO in WSNs to increase energy efficiency when designing WSNs under the Rayleigh flat fading channel.

The content of this paper is organized as various sections. Section 2 discusses the implementation of V-MIMO in WSNs. Section 3 consists of a brief description of the physical layer specifications of Zigbee at 2.4GHz band. The proposed network transmission scenarios of the V-MIMO technique are explained in Section 4. Section 5 discusses the simulation results of the transceiver model for 2.4 GHz band (i.e. Zigbee transceiver) and Rayleigh flat fading. The energy efficiency of WSNs versus different Signal to Noise Ratio (SNR) was simulated using MATLAB. Finally, conclusions based on the simulation results are presented in Section 6.

## **2. RELATED WORKS**

Many researchers have investigated the V-MIMO as a transmission strategy for limited resources WSNs. Authors in [9] studied the throughput of MIMO nodes which were based on the slotted Aloha communication channel. The results of their investigation showed how MIMO could reduce the power consumption for ad hoc tactical networks. In addition, the throughput of MIMO

increases linearly with the number of parallel channels. Authors in [10] investigated the effect of certain distances between nodes on the total delay and the power consumption of WSNs. They studied different MIMO modulation schemes and transmission scenarios for the purpose of allowing nodes cooperation which reduced the transmission power consumption. The use of V-MIMO increases the distance between nodes and reduces power consumption for a large sensing field which requires long distance transmissions [11].

Authors in [12] investigated the power allocation of V-MIMO in WSNs. Their investigation shows that the use of V-MIMO can achieve performance similar to that of actual MIMO for low SNR. According to [13], when multiple senders transmit to a single receiver which is located in the nearby cluster, power consumption can be reduced by selecting appropriate co-operative transmitter nodes. The authors investigated power consumption over both AWGN and Rayleigh flat fading channels when transmitting data packets for intra-cluster and inter-cluster communication scenarios. Joint V-MIMO and data gathering for WSNs is proposed in [14]. In this work, the authors proposed an algorithm (i.e. vMDG) which decreased the power consumption by 36% compared to the MIMO- LEACH algorithm implemented in WSNs.

### 3. THE PHYSICAL LAYER SPECIFICATIONS

Among the frequency bands which are specified for IEEE 802.15.4, one of popular frequency bands is 2.4 GHz due to its availability to all over the world which is free unlicensed ISM band [15]. The specifications of IEEE 802.15.4 Zigbee transceiver which is based on 2.4 GHz band is summarized in table 1 [16].

Table 1: Zigbee Transceiver Specifications

Parameter	Value
Data rate	250 Kbps
Number of Channels	16
Operating frequency	2.4 GHz
Channel spacing	5 MHz
Spread spectrum	DSSS
Chip rate	2 Mega chip per second
Modulation	OQPSK with half sine pulse shaping

The block diagram of physical layer specifications of IEEE 802.15.4 2.4GHz is illustrated in figure 1 which can be summarized in the following [15]:

- Mapping of 4 bits of the 250 kbps into a symbol which generates 62.5 kilo symbol/second.
- Mapping of a symbol to 2 Mega chip/second. This can be used for the purpose of converting a narrow band signal into wide band signal.
- The pulse shaped signal is modulated and transmitted. The modulation scheme is OQPSK at 2.4 GHz frequency band.

- The signal transmitted over AWGN and Rayleigh flat fading channel.
- The received signal follows the reverse process. i.e. demodulation, de-spread and decode.

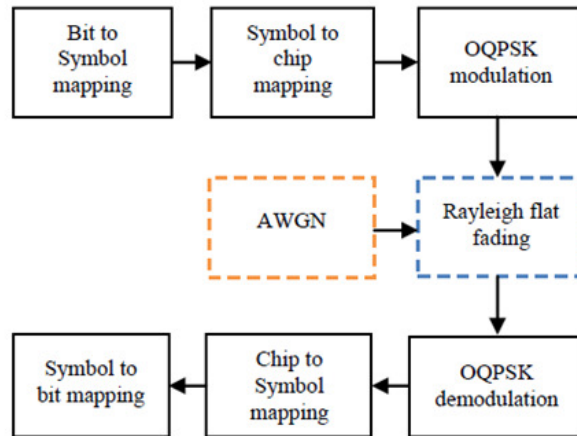


Figure 1. Zigbee 2.4GHz PHY model

#### 4. NETWORK TRANSMISSION SCENARIOS

In our proposed network transmission we have two scenarios which are explained in the following subsections. Both scenarios are designed for a WSN which is interconnected by Zigbee physical layer as described in section 3 and V-MIMO for all sensor nodes.

##### Scenario One: V-MIMO (Multi-hop Transmission)

In this scenario we deploy one rechargeable relay node at the center of the sensing field which is responsible for receiving data packets from the source node, decode and forward them to a destination node. Sensor nodes are randomly distributed into the sensing field. Therefore, this scenario is based on multi-hop transmission. In order to increase the energy efficiency of multi-hop transmission for our proposed WSN, we assume the following:

- Homogeneous sensor nodes which have the same initial energy.
- We assume that all sensor nodes have identical capabilities for sensing, communication and computation.
- One rechargeable relay node is deployed at the center of sensing field.
- Sensor nodes are randomly distributed into the sensing field.
- Three transmitters which are located in different parts of the sensing field send their data packets to three destinations.
- If a sensor node receive a data packet, the destination address will be checked which is explained in the header of a packet. If the node receives a packet which is intended to another sensor node, the packet will be transmitted to the next node in the transmission path. The packet will be accepted at the node if it is the destination node.
- The multi-hop transmission follows the shortest distance to the relay node. It is the algorithm which calculates the node's position in the routing tree while computes the least-cost path (the shortest path) of the source nodes towards the centralized relay node.
- Once the packets received by the centralized relay node, it will be transmitted directly to the destination node which is located far away from a sender.

Figure 2 illustrates the first scenario where each transmitter sends their packets to three receivers (i.e. 3TX-3RX). For example, as shown in figure 2, node 1 (S1) sends their packets

to destination 1 (D1) which is located very close to the sender (the blue links in figure 2). Node 2 (S1) and node 3 (S3) sends their packets to destination 2 (D2) and destination 3 (D3), respectively. D2 and D3 are located far away from the transmitters (i.e. S1 and S2). So the nodes in the path between the transmitters and receivers will follow shortest path algorithm (i.e. the shortest distance to the central relay node) for their packets transmissions to the relay node which transfers these packets to the intended receivers (i.e. D2 and D3) directly (the green and red links in figure 2, respectively).

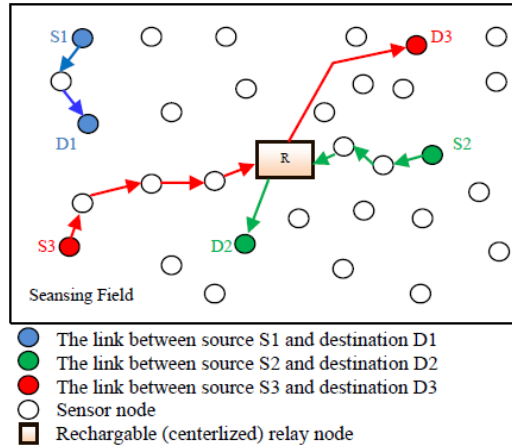


Figure 2. Scenario one, V-MIMO (Multi-hop transmission)

### Scenario Two: V-MIMO (Clusters with Direct Transmission)

In this scenario we divided the sensing field into four clusters where each cluster has a rechargeable (centralized) relay node which transfers data packets using direct transmission to a destination node in the same cluster or any other cluster. In order to increase the energy efficiency of clusters with direct transmission for our proposed WSN, we assume the following:

- Homogeneous sensor nodes which have the same initial energy.
- We assume that all sensor nodes have identical capabilities for sensing, communication and computation.
- The sensing field is divided into four clusters.
- Four rechargeable relay nodes are deployed at the center of the four clusters.
- Sensor nodes are randomly distributed into the four clusters. We assume similar number of sensor nodes in each cluster.
- If a sensor node in a cluster sends their packets, they will be transferred using direct communication to the centralized relay node which is responsible for transferring these packets to a destination node in the same cluster, or relaying the packets to another centralized relay node when the destination is not located in the same in cluster.
- All centralized relay nodes have prior knowledge of all addresses of nodes in their clusters. Thus, if a packet is intended to a destination in outer cluster, the relay node will send the packet to all other relay nodes, the one which have the correct address of the destination node will accept the packet and forward it to the destination, and other relay nodes will drop that packet.

Figure 3 illustrates the second scenario where each transmitter sends their packets to three receivers (i.e. 3TX-3RX). For example, as shown in figure 3, node 1 (S1) in cluster 1 sends their

packets to its relay node which is responsible for transferring these packets to the destination 1 (D1) which is located in the same cluster (the blue links in figure 3). Node 2 (S2) in cluster 2 sends their packets to its relay node (i.e. R2), but the destination node (i.e. D2) is located in cluster 3. So, the relay node (R2) sends their packets to all relay nodes (i.e. R1, R3, and R4). Here, relay node 3 (R3) will accept these packets and forward them the destination node its cluster 3. Relay nodes 1 and 4 (i.e. R1 and R4) reject these packets (the green links in figure 3). Node 3 (S3) in cluster 4 sends their packets to its relay node (i.e. R4), but the destination node (i.e. D3) is located in cluster 2. So, the relay node (R4) sends their packets to all relay nodes (i.e. R1, R2, and R3). Here, relay node 2 (R2) will accept these packets and forward them the destination node its cluster 2. Relay nodes 1 and 3 (i.e. R1 and R3) reject these packets (the red links in figure 3).

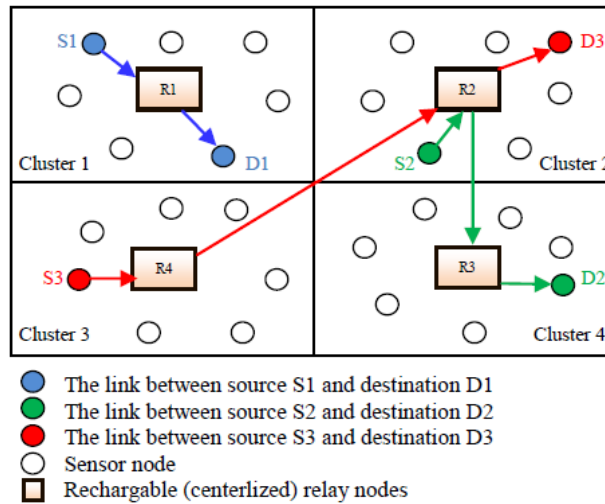


Figure 3. Scenario two, V-MIMO (Clusters with Direct Transmission)

## 5. SIMULATION RESULTS

In this section we present the simulation results of our proposed V-MIMO with the two transmission scenarios when packets were transmitted over Rayleigh flat fading channels.

### Simulation settings and parameters

We simulated a static WSN which consisted of 32 sensor nodes that distributed randomly in the 50x50m sensing field. The rechargeable relay nodes were located either at the centre of the sensing field for the first transmission scenario or at the centre of the four clusters for the second transmission scenario. In addition, we assumed the Zigbee physical layer using IEEE 802.15.4 specifications as described in Table I. Also, we considered the effect of the Rayleigh flat fading communication channels. The simulation results were obtained via MATLAB simulator. The simulation settings are summarized in Table II.

The performance parameter that is presented in this section is energy efficiency ( $\hat{E}$ ) which can be described as the ratio of energy consumption of a sensor node (or a transceiver) when sending/receiving actual data packets ( $l$ ) to the energy consumption of a sensor node when sending/receiving data packets for the proposed system model ( $\mathcal{E}$ ). This ratio is multiplied by the reliability of transmission between a sender and a receiver ( $\check{R}$ ) as shown in Equation 1.

$$\hat{E} = (l/\mathcal{E}) \times \check{R} \tag{1}$$

Table 2. Simulation Settings

Sensing field	50 m x50m
Number of sensor nodes	32 sensor, equal number of sensors in each cluster in the second scenario.
The rechargeable relay node(s) location	(25,25) for first scenario  (12.5,12.5) cluster 1, second scenario  (37.5,12.5) cluster 2, second scenario  (37.5,37.5) cluster 3, second scenario  (12.5,37.5) cluster 4, second scenario
Number of transmitted packets	300 packets
Number of transmitted data bits per packets	3000 bits
SNR	Range between -20dB to 20B
Operating frequency	2.4 GHz
Channel spacing	5 MHz
Spread spectrum	DSSS
Chip rate	2 Mega chip per second
Modulation	OQPSK with half sine pulse shaping
Initial energy for a sensor ( $\hat{i}$ )	0.5 J

### Simulation Results and Analysis

In this section, we present and analyse detail the simulation results for the proposed V-MIMO under the two transmission scenarios. As described in Section IV, in both transmission scenarios the networks model has three node transmitters and three node receivers (3TX-3RX).

- For the Rayleigh flat fading channel and the first transmission scenario which is based on V- MIMO and multi-hop transmission, the energy efficiency is shown in Figure 4. The simulation results indicate that the best energy efficiency is achieved when the source node (S1) sends its packets to the destination (D1) for SNR between -20dB and 20dB. This is because the destination D1 is located in proximity to the transmitter (S1) in the transmission path. It is followed by the case when the source node (S2) sends its packets to the destination (D2) via the relay node (R) for SNR between -20 dB and 5 dB. The lowest energy efficiency is for the case when the source node (S3) sends its packets to the destination (D3) for the same SNR range. This is because packets need to be transferred via multi-hop transmission over many sensor nodes in the path between the transmitter (S3) and the receiver (D3), which results in higher consumptions of power.
- For the Rayleigh flat fading channel and the second transmission scenario which is based on V-MIMO and clusters with direct transmission, the energy efficiency is shown in Figure 5.
- The simulation results indicate that the best energy efficiency is when the source node (S1) sends its packets to the destination (D1) for SNR between -20 dB and 20 dB. This is

because the destination D1 is located in proximity to the transmitter (S1) in the same cluster (i.e. cluster 1). It is followed by the case when the source node (S3) in cluster 4 sends its packets to the destination (D1) in cluster 1 via the relay nodes (R1 and R4) for SNR between  $-20$  dB and  $0$  dB, and the case when S2 sends to D3 for SNR between  $0$  dB and  $20$  dB. The lowest energy efficiency is for the case when the source node (S3) sends its packets to the destination (D3) via R4 and R2.

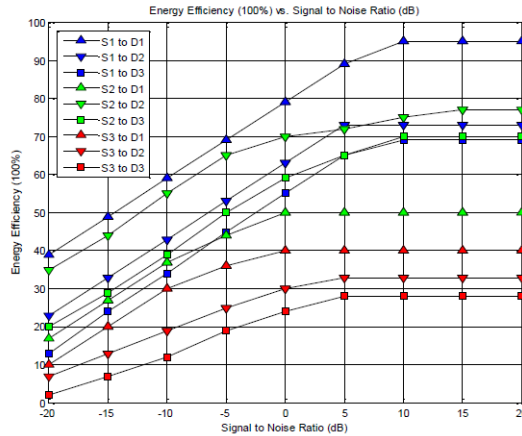


Figure 4. Scenario one, Energy Efficiency vs SNR

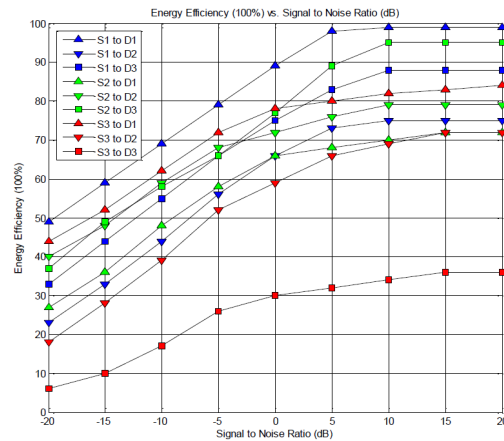


Figure 5. Scenario two, Energy Efficiency vs SNR

## 5. CONCLUSION

Power consumption is a critical issue for limited energy resources networks such as WSNs. In this work, we have designed WSNs which took the advantage of using the V-MIMO technique (i.e. by reducing the multipath fading channel) along with Zigbee physical layer specifications. In addition, we have proposed two transmission scenarios for the purpose of increasing the energy efficiency. The first scenario is based on multi-hop transmission which has lower energy efficiency compared to the second transmission scenario which is based on dividing the sensing field into clusters and using direct transmission via centralized relay nodes. Our simulation results have shown different SNR ranges for the highest and the lowest energy efficiency when the network model has had three transmitters and three receivers (3TX-3RX). These results were discussed with respect to the scenario when packets were transmitted over the Rayleigh flat fading channel.



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