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Virtual Sensing Directional Hub MAC (VSDH-MAC) Protocol with Power Control

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Abstract: Medium Access Control (MAC) protocols play a vital role in making effective use of a multiple access channel as it governs the achievable performance such as channel utilization and corresponding quality of service of Wireless Sensor Networks (WSNs). In this paper, a virtual carrier sensing directional hub (VSDH) MAC protocol incorporating realistic directional antenna patterns is proposed for directional single hub centralized WSNs. While in most instances MAC protocols assume idealized directional antenna patterns, the proposed VSDH-MAC protocol incorporates realistic directional antenna patterns to deliver enhanced link performance. We demonstrate that the use of directional antennas with a suitable MAC protocol can provide enhanced communication range and increased throughput with reduced energy consumption at each node, compared to the case when only omnidirectional antennas are used. For the scenarios considered in this study, results show that the average transmit power of the sensor nodes can be reduced by a factor of two, and at the same time offer significantly extended lifetime.

Keywords: Medium Access Control (MAC), Wireless Sensor Network (WSN), Wireless Communication, Directional Antennas, Energy Efficiency, Power Control.

1. Introduction

Wireless Sensor Networks (WSNs) have been employed in a wide range of health care, industrial and environmental monitoring applications [1-3]. For many applications, the use of batteries in sensor nodes places constraints on the energy budget, so it is important to maximize the performance of the network whilst minimizing the sensor node energy consumption. Interference, lack of fairness and energy consumption are the key constraints in WSNs, which poses challenges to the design of Medium Access Control (MAC) protocols. Directional antennas provide the potential to increase transmission range and/or reduce transmission power, to reduce interference along with the prospect of allowing spatial reuse. In order to make the best use of directional antennas, suitable MAC protocols must be designed.

On selection of suitable MAC protocols for WSNs, one could consider either contention-based or contention-free protocols. Contention-based protocols can be less efficient than those without contention in terms of throughput performance for large star topologies due to the large number of collisions when the data traffic offered load is high. However, they are simpler and typically provide lower delay in smaller WSNs [4]. Contention-based protocols are a promising approach for directional MAC protocols, as they enable multiple nodes to simultaneously access a channel without the need for synchronization. Scheduling and synchronization are the main challenges for contention-free protocols, especially for WSNs with mobile nodes and/or a varying number of nodes.

In [5], we proposed a simple directional hub MAC protocol for star topology WSNs based on the Pure Aloha protocol, in which the performance differences between a realistic directional antenna pattern and idealized directional antenna pattern were demonstrated. It is shown that although directional antennas can provide high throughput performance, the antenna pattern may still have a significant effect on spatial reuse and network performance. In this proposed protocol, node complexity and power consumption are minimized by having only a single omnidirectional antenna on the basic sensor nodes. The Hub carries multiple directional antennas and can be continually powered as its complexity and power consumption are not considered critical compared with the basic sensor nodes. Energy consumption and fairness were considered in [6], in which a MAC protocol with transmit power control on nodes was analysed. The performance enhancement that can be achieved by the use of power control and directional hub antennas was demonstrated, in terms of network throughput, node power consumption, and fairness.

Most previous works on the use of directional antennas have assumed the use of idealized antenna patterns where each antenna beam is distinct, with no overlap with adjacent beams and having a constant antenna gain across the beam [7-15]. Some work has assumed that the nodes are capable of knowing each other's position [7,9-11] or that nodes have complex, steerable antennas [7,12]. Also multiple antennas are often required at the nodes as well as the hub [7-13,16] which increases both the complexity and energy consumption of the nodes. Some of the protocols proposed also require multiple channels to successfully operate [8,13,16]. Only a few papers within the literature [14,17-19] have considered the energy consumption of the protocol, which is an important factor for low power nodes [20].

In this paper, a modified directional CSMA/CA (carrier sense multiple access with collision avoidance) protocol is proposed, which is similar to the IEEE 802.11 WI-FI standard and the IEEE 802.15.4 standard for WSNs. A version without the traditional physical carrier sensing is used (to reduce energy consumption). Here virtual carrier sensing is performed via handshaking packets. A version with physical carrier sensing similar to the CSMA/CA protocol is also considered for comparison. The hub node is equipped with multiple directional antennas, and the channel is efficiently utilized through the benefits of spatial reuse. A dynamic transmit power control algorithm is employed at the wireless sensor nodes to improve node energy efficiency. A uniform signal-to-interference-plus-noise ratio (SINR) is achieved for packets from all sensor nodes in the network. As shown through simulations, the proposed protocol leads to improvements in network throughput, energy consumption, and fairness performance. The effects of antenna pattern overlap are also significantly reduced by the proposed protocol.

The rest of the paper is organized as follows: In Section 2 we describe the network topology and proposed MAC protocol in detail. In Section 3 we describe the simulation methodology and in section 4 we present results that show the improved throughput and performance that can be achieved, along with the effect of the antenna gain, power control algorithm, and antenna pattern.

2. Medium Access Control Protocol

This section outlines the operation of the Virtual Sensing Directional Hub MAC protocol (VSDH-MAC) and the carrier sensing version (DIFS-VSDH-MAC).

The proposed VSDH-MAC protocol is similar to the IEEE 802.11 DCF (Distributed Coordination Function), which uses CSMA/CA/DCF protocol [21], and the IEEE 802.15.4 protocol which is a CSMA/CA protocol. However, continuous physical channel sensing is not performed. Instead, virtual channel sensing is enabled using Request-To-Send / Clear-To-Send (RTS/CTS) packets in a similar way to the CSMA/CA/DCF protocol. The packet exchange procedure of the VSDH-MAC protocol follows the IEEE 802.11 CSMA/CA/DCF method with the RTS/CTS and DATA/ACK (data / acknowledgement) packet structure.

In this paper, we consider a network with a single hub node which has a number of directional antennas which can operate simultaneously, each in half-duplex (HDX) mode. The power consumption of the hub node is not considered to be constrained. The sensor nodes are assumed to have a single omni-directional antenna to reduce hardware complexity. It is assumed that the transmit power of each sensor node can be adjusted to minimise the transmit power consumption and inter-node interference. Furthermore, we assume that all communications are initiated by the sensor nodes so that they can remain quiescent and minimise energy consumption when they have no data to transmit.

2.1 VSDH-MAC Channel Access Algorithm

When a node has no data packet to transmit, i.e. its packet queue is empty, it will remain in sleep state to conserve energy. When a node wishes to transmit a data packet, it will send a short RTS packet to the hub immediately, using its maximum transmit power. The maximum transmit power is used because we have assumed sensor nodes might move, and we require the RTS to reach the hub regardless of the current node position, which is assumed unknown. Extensive simulations implemented in Riverbed Modeler have shown that although the RTS packets are sent with maximum power, there is no significant impact to the node energy consumption and overall network throughput. If it receives a CTS packet from the hub, in response to the RTS packet, it may then transmit a data packet to the hub. The node is assumed to know the hub transmit power and uses the received power of the CTS to compute the path loss and thereby choose the least required packet transmit power to successfully transmit the data packet, assuming a reciprocal channel. This is done in order to minimize both the interference to other nodes and the node power consumption, although it is of course simple to introduce an appropriate link margin by increasing the transmit power above the calculated minimum if desired, to account for uncertainties and variation in the channel, e. g. due to shadowing. In this study, we assumed the same background noise at both the transmitter and receiver. In a real network, while the reciprocal path is the same, the noise might not. Hence, in a practical protocol it would be necessary for the hub to calculate the required transmit power with its background noise and include the value in the CTS as a reference for the sensor node. RTS and CTS packets both contain a network allocation vector (NAV) which defines the time required to complete the subsequent data packet transmission and associated handshaking. Other nodes hearing a CTS above a certain amplitude threshold will delay their transmission to avoid collision. The threshold is defined as the product of the packet transmit power and the receiving antenna gain at angle θ (G_θ), where $\theta = \frac{360}{M}$, and $\boldsymbol{M}$ is denoted as the number of directional antenna at the hub. Nodes only listen for a CTS during the time when they are awaiting a reply for their own RTS. This also maximizes the chance of avoiding collisions between active nodes, whilst minimizing node energy consumption, as a node does not need to listen for a CTS except when it is likely to be transmitting data. After sending an RTS the node waits for a time slightly larger than the expected round trip time (RTT). If a node receives no response to its RTS within this time, it will enter a backoff state which delays transmission of another RTS for the same data by a random delay in the range [0, $CW - 1$] where CW is an interval called the Contention Window. Subsequent failures to receive a CTS increase the backoff time range exponentially by a factor of 2 in each case. The value of the random backoff interval is chosen from the CW, which lies between two preconfigured values, CW_min and CW_max. The values for these are identical to the IEEE 802.11 CSMA/CA/DCF protocol. The contention window is set to CW_min at the first transmission attempt, and doubles after each unsuccessful attempt, until it reaches CW_max. The contention window is reset to CW_min after every successful transmission. After the counter reaches CW_max the packet transmission would be abandoned, and the error would also be reported to the layer above. Once a packet is transmitted, if an acknowledgment is not received within the specified RTT time for the data packet, a re-transmission with maximum transmission power for the data packet will be performed following the same RTS/CTS/DATA/ACK sequence. Thus, the node protocol is designed to require minimal electrical and processing power.

Operation of the protocol at the hub is slightly more complex as it has multiple antennas and corresponding transceivers. The hub algorithm differs in the following manner. It is assumed to be capable of communicating via all antennas simultaneously and listening continuously from any that is not transmitting. It is assumed that the hub will not initiate a transmission to the node. If transmission of messages from the hub to the nodes is required, it can be included in the ACK packet at the end of each exchange. If the hub receives an RTS on one or more antennas from a node it will note which of the antennas provides the highest SINR and use that antenna for subsequent communications with the node until a packet arrives at a different antenna with higher SINR from the same node. If the hub has received the same packet from multiple antennas with equal SINR, then the subsequent transmission will use a random antenna selection between them until an optimum antenna is established. When an RTS is received from a node, and if no other RTS has reserved the optimum antenna, the hub will reserve the optimum antenna for a period indicated as NAV (network allocation vector) in the RTS (NAV) and then transmit a CTS to the node from the optimum antenna. The CTS also contains a NAV which will cause any listening node to delay its transmission. As nodes do not continuously listen there is still a probability of collision by a node that does not hear the ongoing exchange when it is ready to transmit.

A modified VSDH-MAC protocol with an additional physical channel sensing (DIFS long) is also considered in this paper (DIFS-VSDH-MAC), in which nodes sense the channel prior to transmission of an RTS. If any signal above the SIR threshold is received, it will pause the DIFS counter and enter the backoff stage according to the NAV. This improves the overall throughput performance of the protocol y reducing the probability of RTS/CTS collision, at the cost of increased sensor node energy consumption and transmission delays.

Algorithm 1 VSDH-MAC protocol with power control algorithm. cd_CW is the number of contention window, cd_RTS, cd_DATA are counters for sensor nodes after transmitting RTS and DATA packets respectively, cd_NAV is a counter based on the NAV from the overheard packet, CW_max is the maximum value for contention window.

```
for each packet arriving queue do
  while cd_CW = 0 do
    if ongoing transmission = 0 then
      Send RTS to receiver
      Start countdown timer (cd_RTS)
      if CTS received && cd_RTS > 0 then
        update P_tx based on the CTS received power
        Send DATA to receiver
        Start countdown timer (cd_DATA)
        if ACK received && cd_DATA > 0 then
          Packet transmission successful
        else
          Update P_tx to maximum
      else if CTS for other nodes received && cd_RTS >0 then
        Update cd_NAV based on overhead CTS
        cd_CW = a random CW value (where CW = [ 0, CW_max – 1]
        Start countdown timer (cd_CW = cd_NAV + cd_CW)
      else
        Update P_tx to maximum
        cd_CW = a random CW value (where CW = [ 0, CW_max – 1]
        Start countdown timer (cd_CW)
```

3. Simulation Methodology

3.1. Network Configuration

To fairly characterise the performance of the protocols, a series of randomly generated configurations are considered, an example is shown in Figure 1. We chose a single hop star topology with half duplex (HDX) operation on a single frequency channel as this is simple and common in WSNs. A HDX operation is defined a system supporting communication in both directions, but only one direction at a time. A 2-dimentional distribution of sensor nodes is considered in the study. The star topology allows for a continuously powered hub where energy usage and complexity are not considered to be an issue. By adding directional antennas to the hub, we can improve throughput, and range or energy consumption. We consider n nodes randomly distributed in a 100 x 100 m^2 grid, where the x and y-coordinates are each chosen using a pseudorandom number generator with a uniform distribution between plus and minus 50 m. The single hub base station node is positioned at the centre of the grid.

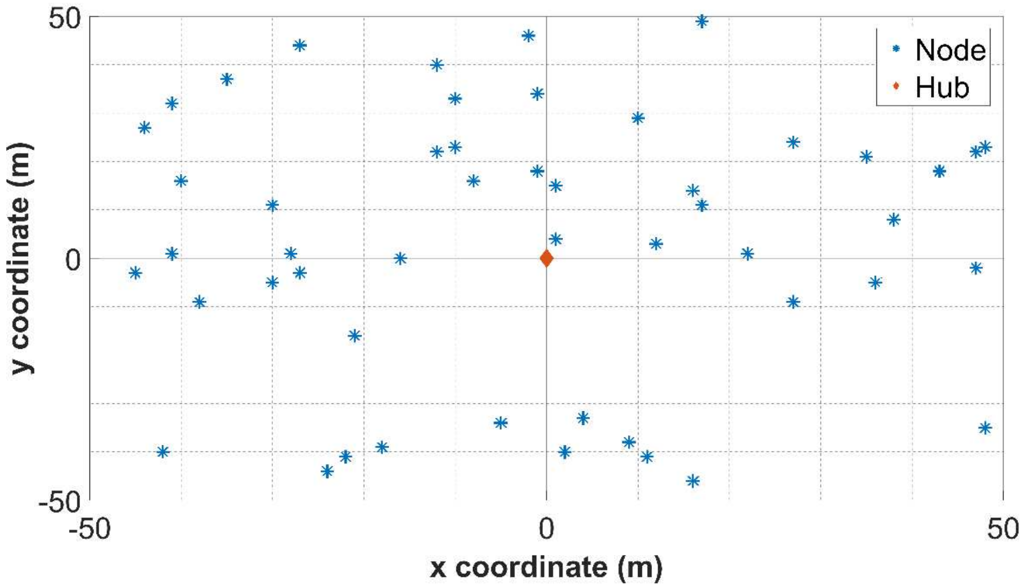

Figure 1. An example of centralized WSNs topology.

3.2. Simulation Setup

To evaluate the performance of the proposed protocol, simulations have been performed using Riverbed Modeler (formerly known as OPNET) [22]. In all simulations, we consider only free space propagation as an illustrative example. We chose to use 4 antennas ass a reasonably practical number to illustrate the performance of a multi-antenna hub. Fewer antennas could be used with litter effort. However, if a significant increase in the number of antennas were required, the issue of beam overlap may become a significant problem. Some overlap is necessary as it is not possible to design antennas with ideal cutoff at the beam edges, but as described in [5], beam overlap is a significant factor in limited the throughput performance. As the sector angle decreases with increasing numbers of antennas, the degree of overlap must be reduced by the same amount to maintain the same performance per antenna. We suspect this will create some practical difficulties in antenna design and alignment.

The transmission parameters are shown in Table 1. Note that SIFS and BPSK, in Table 1 stand for Short Interframe Space and Binary Phase Shift Keying, respectively. The simulator uses the SINR to determine the bit error rate (BER). This BER value is used to determine if each individual bit is received in error, assuming randomly distributed errors. A uniformly distributed random number between zero and one is generated randomly. This number is compared with the BER threshold (obtained from a look up table of SINR vs BER for a given modulation scheme), and one or more bit errors will result in a discarded packet. Packets with errors are rejected by the protocol. The data packets are generated according to a Poisson process with a rate (G), which is referred as the channel offered load or traffic load. The Poisson arrival process gives an exponentially distributed inter-arrival time of the data packet generation.

Table 1 Transmission parameters

Parameters	Values
Frequency band	2.4 GHz
Channel bit rate	250 kbit/s
RTS, CTS, ACK length	8 bits
Data length	1024 bits
Number of Hub Antenna (M)	4
Maximum Transmission Power	0.052 W
Node Received Power	0.059 W
Node Sleep Power	0003 mW
Digital modulation	BPSK
CW_min	31
CW_max	1023
SIFS	10 us

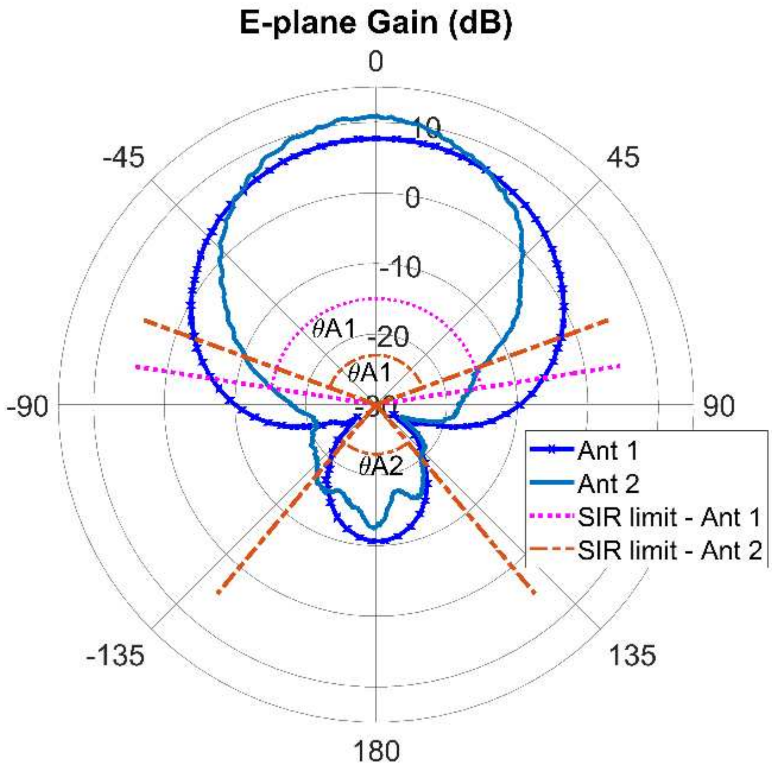

Figure 2. Polar plot of antenna gain pattern for Ant 1 and Ant 2 with its SIR (signal-to-interference ratio) limit angles, where $\theta_A = \theta_{A1} + \theta_{A2}$.

3.3. Directional Antennas

In order to demonstrate the effect of antenna pattern on performance, simulations were performed with two real antenna patterns. Antenna 1 (Ant 1) is based on a 3 element Yagi design and the second antenna (Ant 2) is based on the low cost antenna from [23], as demonstrated in Figure 2.

Also, we consider an ideal sectored antenna with uniform gain over a 90° sector and zero elsewhere as commonly used in other studies. Detailed discussion on SIR limit analysis can be found in [5].

3.4. Energy Consumption Calculation

This section provides the average energy consumption analysis of the proposed VSDH-MAC protocol. The average energy consumption during data transmission, reception and control packets is given below.

Successful data packet transmission (E_{tx}):

$$E_{tx} = P_{tx_{RTS}} T_{RTS} + P_{tx_{DATA}} T_{DATA} + P_{rx} \left(T_{CTS} + T_{ACK} + 2\,x\,(T_p + T_{SIFS})\right), \tag{1}$$

Colliding RTS or CTS transmission (E_{c_RTS}):

$$E_{c\_RTS} = P_{tx_{RTS}} T_{RTS} + P_{rx} \left(T_{CTS} + T_p\right), \tag{2}$$

Colliding DATA or ACK transmission (E_{c_DATA}):

$$E_{c\_DATA} = E_{c\_RTS} + P_{tx_{DATA}} T_{DATA} + P_{rx} \left(T_{ACK} + T_p + T_{SIFS}\right), \tag{3}$$

Backoff due to unsuccessful RTS/CTS communication (E_{BO}):

$$E_{BO} = E_{c\_RTS} + P_{sleep} (T_{CW}), \tag{4}$$

Overhearing reception destined to other user after RTS transmission, (E_{OH}):

$$E_{OH} = E_{c\_RTS} + P_{rx} (T_{SIFS}) + P_{sleep} (T_{NAV} + T_{CW}), \tag{5}$$

Sleep when no packet transmission is required (E_{sleep}):

$$E_{Sleep} = P_{Sleep} T_{Sleep}, \tag{6}$$

In addition, when carrier (DIFS) sensing is used, additional energy (E_{DIFS}) is consumed:

$$E_{DIFS} = P_{rx} T_{DIFS}, \tag{7}$$

where T_{DIFS} is the time during which the carrier is sensed. If a transmission is detected during T_{DIFS} then additional energy is expended (E_{OH_DIFS}) whilst the node waits before attempting to transmit again:

$$E_{OH\_DIFS} = E_{DIFS} + P_{sleep} (T_{NAV} + T_{CW}), \tag{8}$$

where, P_{sleep}, $P_{tx_{RTS}}$, $P_{tx_{DATA}}$, and P_{rx} are the power consumed in sleep, transmit and receive mode respectively. T_{SIFS}, T_{DIFS} and T_P are the SIFS and DIFS time duration from IEEE 802.11 DCF standard and the propagation time of the packet. T_{CW} is the backoff time duration. T_{RTS}, T_{CTS}, T_{DATA}, and T_{ACK} denotes the packet transmission time for RTS, CTS, DATA, and ACK packets respectively. T_{sleep} is the time for the node to stay in the sleep state. T_{NAV} represents the backoff time indicated from the received NAV.

Figure 3 shows a breakdown of the average energy consumption per successful data bit in a sensor node with respect to the channel offered load. Figure 3(a) is the energy consumption of the VSDH-MAC protocol with power control strategy. Figure 3(b) is the energy consumption of the VSDH-MAC protocol without the power control strategy. Figure 3(c) is the energy consumption of the IEEE 802.11 DCF protocol. By comparing those figures, it can be seen that the VSDH-MAC protocol provides a far higher energy efficiency than CSMA/CA protocol. Figure 4 shows the additional transmission required for the DIFS sensing. Table 2 shows the operation states of the sensor node and the power consumption of each state. The values are based on typical figures for current radio modules and serve only for comparative purposes.

We expect the number of hub antennas to have a small impact on the node energy usage in a given scenario. Firstly, as the number of nodes in each sector is reduced there is likely to be fewer collisions which would reduce the energy wasted by this mechanism. Also an increased number of antennas would require a narrower beam width per antenna, which implies increased gain in most cases; this would reduce the required transmission power for both the nodes and the hub in a given scenario

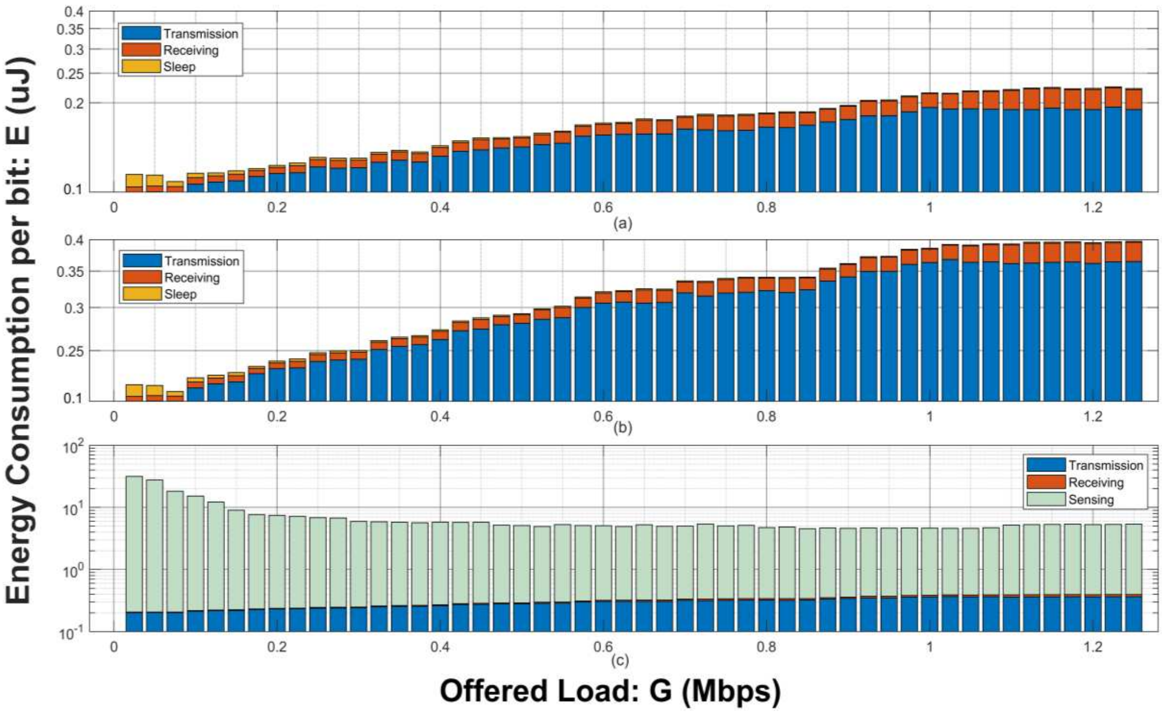

Figure 3. The comparison of required transmission energy per bit VSDH-MAC protocol with power control (a) and without power control (b), and CSMA/CA/DCF protocol (c).

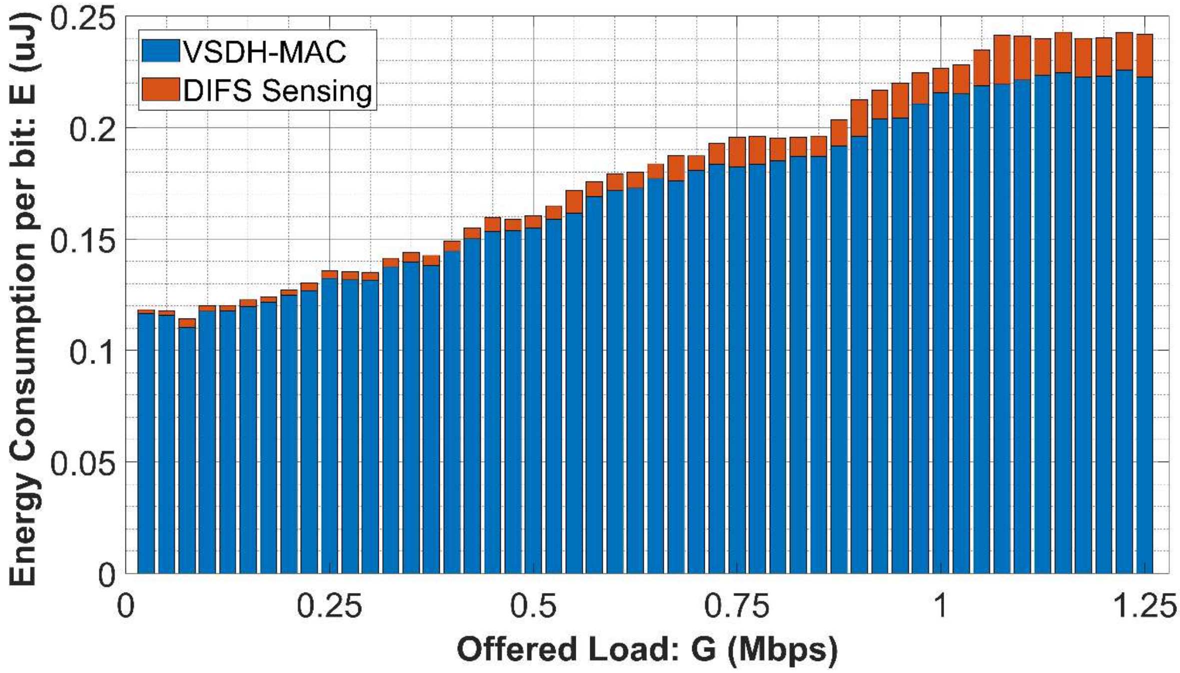

Figure 4. The transmission energy per bit for a four antennas DIFS-VSDH-MAC protocol showing the proportion of energy used by DIFS sensing.

Table 2. Operational States for FSM of Sensor nodes

State	Activity	Tx	Rx	Power Required
S_0	Sleep	Off	Off	0.003 mW
S_1	RTS Tx	On	Off	52 mW
S_2	Receiving	Off	On	59 mW
S_3	Data Tx	On	Off	26 mW (Average)

4. Results Analysis

The offered load is distributed evenly across all of the sensor nodes. The network throughput is the channel capacity successfully used by all sensor nodes with the maximum of $\boldsymbol{M}$ Erlangs, in which $\boldsymbol{M}$ is the number of directional antennas equipped at the hub. For the purpose of understanding the link performance of the protocol, the results will be expressed as the total number of data bits successfully received per unit time.

Figure 5 shows the throughput of directional hub Aloha (DH-Aloha) protocol [5] averaged over 10 randomly generated networks for each of the three directional antenna types. As predicted in our previous work [5], the antenna pattern has a significant effect on throughput. The idealized antenna pattern with no overlap between sectors, shows a substantially larger throughput than can be achieved with the real antennas with patterns that have some overlap. As depicted in Figure 4, due to the shape of the antenna pattern, the reason that Ant 1 has a higher throughput than Ant 2 is due to the fact than although Ant 2 has a narrower beamwidth, it has a larger back lobe. Using the analysis in [5], the back lobe increases the overlapping ratio (r), as θ_A increases. This results in more packet collisions caused by interference from antenna patterns overlapping.

In Figure 6, the throughput of the VSDH-MAC protocol for Ant 1 and Ant 2 is presented. The difference between the throughputs of the two antennas are significantly smaller than in Figure 5. This is because the power control mechanism reduces the effect of antenna pattern overlap by adjusting the node transmission power. The adjusted transmission power reduces the interference caused by the back lobe.

It is useful to compare the throughput performance of the VSDH-MAC and DIFS-VSDH-MAC protocols with other directional MAC protocols. Two other directional MAC protocols have been replicated for the purpose of performance comparison. Both protocols have been replicated with the parameters described in section 3. In the DMAC (Directional Virtual Carrier Sensing MAC) protocol proposed in [24], the simulation results showed a saturation throughput of 0.225 Mbps with the same simulation setup as in Section 3. However, it is assumed that all nodes are equipped with beamforming directional antennas and Global Positioning System (GPS). The DMAC protocol is based on the IEEE 802.11 standard and nodes are required to perform channel sensing prior to transmission. The use of GPS and channel sensing has significantly increased the node energy consumption. With idealized antenna patterns, the VSDH-MAC and DIFS-VSDH-MAC protocols can achieve a saturated throughput of 0.336 Mbps and 0.426 Mbps, which is approximately a factor of 1.5 or 1.9 higher than the saturated throughput of DMAC. The CMDMAC (Cooperative Multichannel Directional MAC) is a similar protocol that requires multiple channels [25]. It requires one radio channel for control packets such as RTS, CTS and ACK, and a second radio channel for data transmission. Our simulation results indicate a saturated throughput of 0.45 Mbps from the CMDMAC protocol with the same simulation setup as in Section III and ideal directional antennas. All sensor nodes must be equipped with an omni-directional antenna for overhead communication and an idealized steerable directional antenna for data transmission. The additional channel provides continuous channel sensing which provides advantages in terms of throughout performance. Although the CMDMAC protocol provides better throughput performance compared with the VSDH-MAC protocol, under these conditions, the additional requirements mean that the throughput performance comes at the cost of increased node manufacturing cost and energy consumption. Moreover Figure 7 shows that the throughput performance of applying an idealized antenna pattern is significantly higher than using realistic antenna patterns.

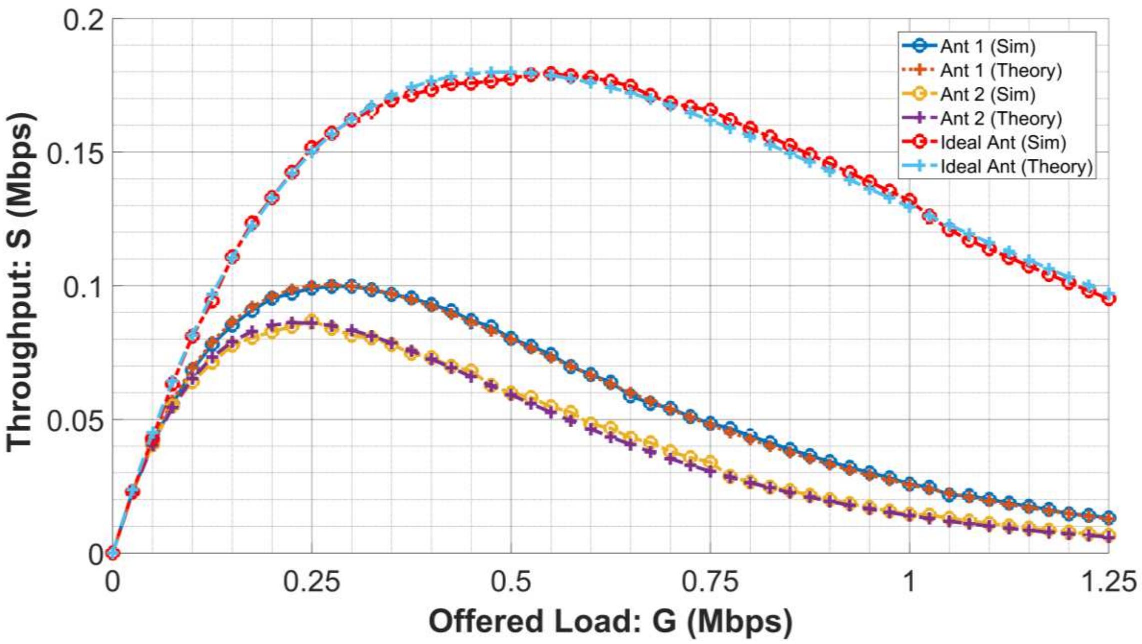

Figure 5. Throughput comparison of different antenna patterns with the DH-Aloha protocol with $M = 4$.

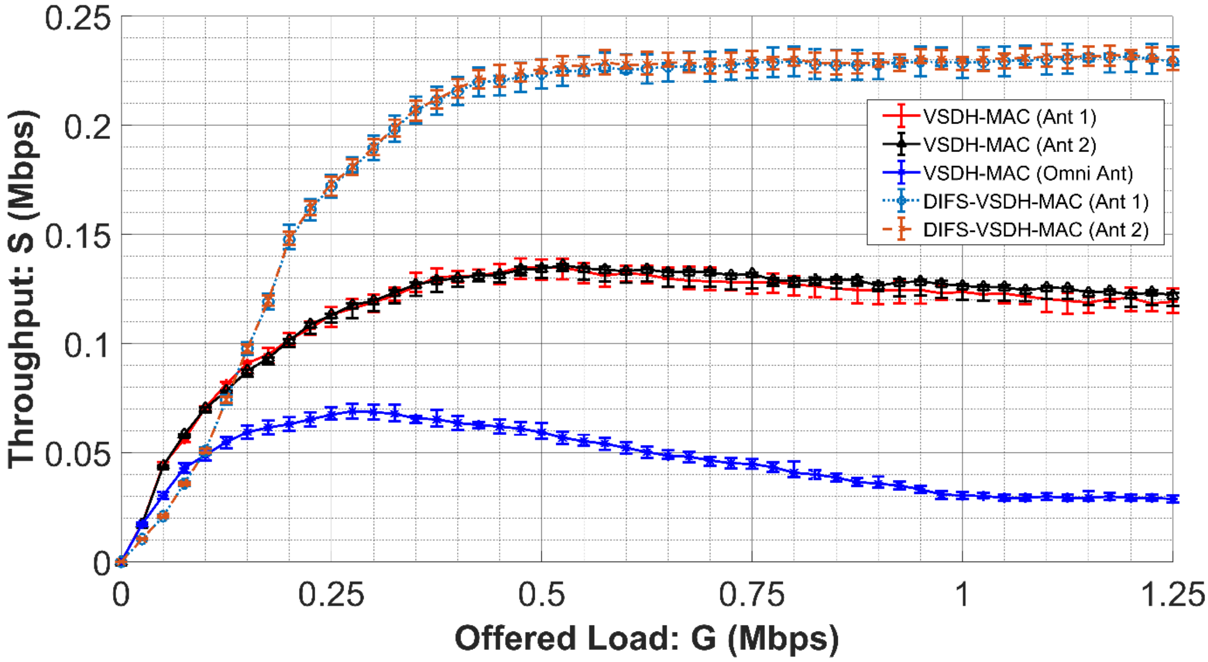

Figure 6. Throughput of the VSDH-MAC and DIFS-VSDH-MAC protocols with different antennas patterns with $M = 4$, compared against the VSDH-MAC with a single omni-directional hub antenna.

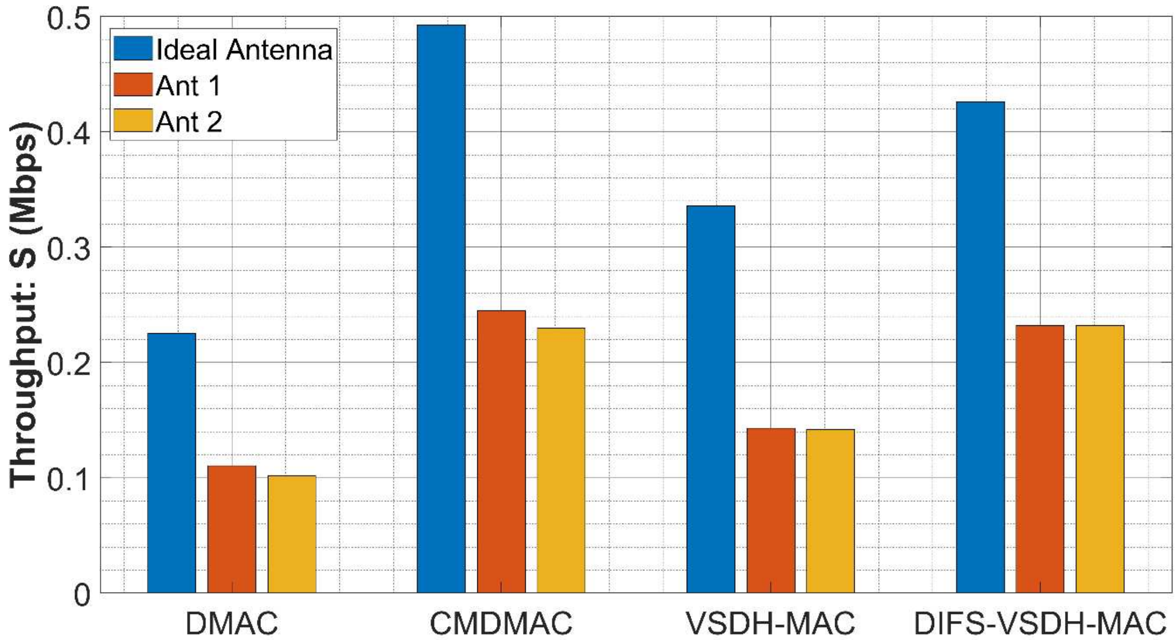

Figure 7. Impact of antenna pattern on throughput performance with $M = 4$.

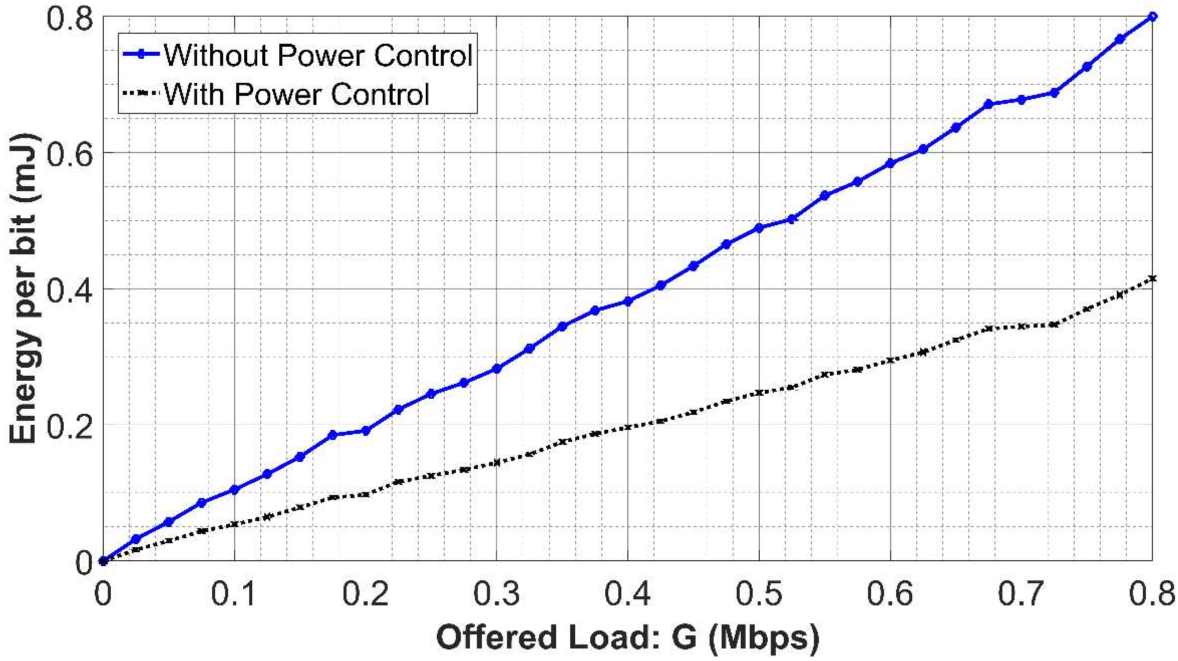

Figure 8. The required transmission energy per bit with and without the proposed power control scheme.

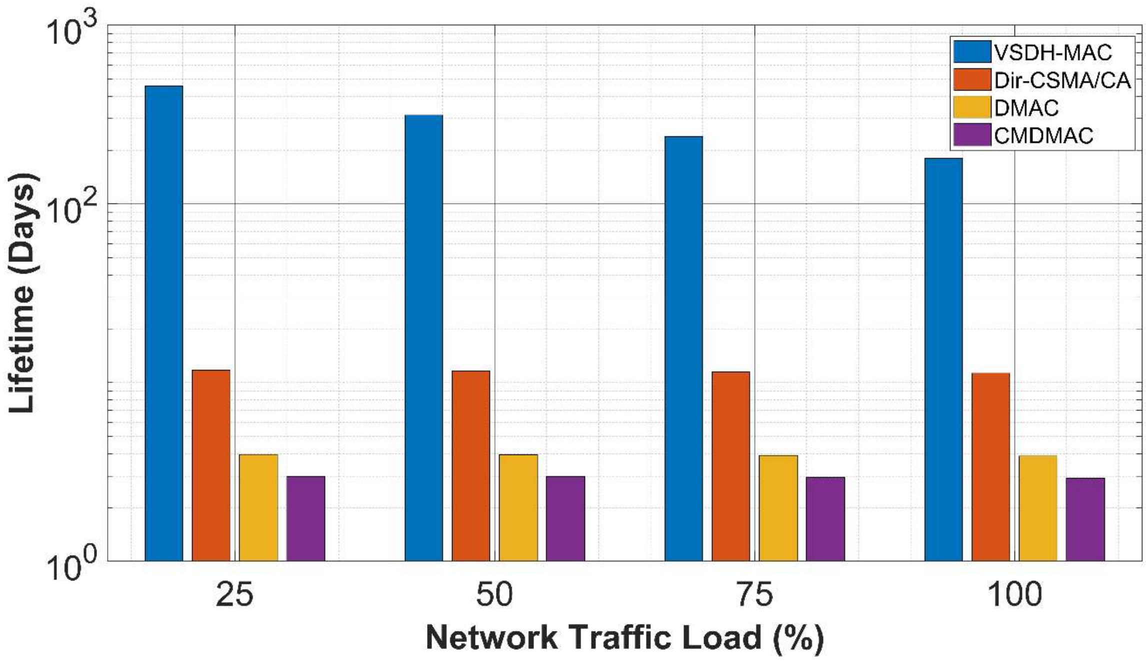

Figure 9. Comparison of expected sensor node lifetime with different network traffic load.

Figure 8 shows the average transmission energy required by the VSDH-MAC protocol with and without power control, for each successful data bit. The power control algorithm can reduce the average required transmission energy by a factor of 2. One of the goals of the VSDH-MAC is to prolong the lifetime of the sensor and hence the network lifetime. To quantitatively compare these directional MAC protocols, we adopt the quoted values of current consumption values from MICAz mote [26]. Two 1.5V batteries rated at 2000 mAh each are assumed for each sensor node. We assume the current draw and the size of the packets are fixed. Figure 9 shows the numerical comparison of the expected lifetime obtained from the directional MAC protocols including the directional CSMA/CA. Figure8 and 9 highlights that the energy efficiency and lifetime expectancy of the VSDH-MAC outperforms the other protocols. Comparing to the VSDH-MAC protocol, the physical carrier sensing from the other directional MAC protocols contribute a significant amount of energy consumption to the sensor nodes. This mechanism with the lack of transmit power control further reduce the lifetime of the sensor nodes. It is important to have an accurate energy model and lifetime estimation of a sensor node, as it directly impacts the lifetime of a WSN.

Figures 10 and 11 show the fairness of the VSDH-MAC protocol. Figure 10 shows the impact of transmission distance on fairness performance and the effect of the power control strategy. It can be seen that the effect of distance on throughput is much less with the power control strategy, thus increasing the fairness of the network. In wireless communication, increasing the propagation distance would increase the path loss in the transmission which may cause the SINR to decrease with distance. However, the power control strategy in VSDH-MAC provides a uniform SINR for all sensor nodes regardless of the propagation distance, thus increasing the per node fairness.

Figure 11 compares the fairness performance of VSDH-MAC protocol and IEEE 802.11 DCF using Jain's fairness index [27]. Jain's fairness index is used to determine the fairness of the network at different offered loads, and is defined by:

$$FI = \frac{(\sum_{i=0}^{n} x_i)^2}{n * \sum_{i=0}^{n} x_i{}^2}, \quad (9)$$

where n is the number of nodes in the network, x_i is the throughput of the i^{th} node within the network. The fairness index ranges from $\frac{1}{n}$ to 1. Ideally, when all sensor nodes share the channel equitably, the fairness index should be equal to 1.

Figure 11 indicates that the VSDH-MAC protocol with the power control strategy achieves a higher fairness index than the case without power control and the directional CSMA/CA. At low offered load, VSDH-MAC provide a very high Jain's fairness index value. This indicates that all sensor nodes within the network have an equal opportunity to transmit a packet to the hub and of being received successfully. At higher offered load values, the value of the Jain's fairness index decreases, as more nodes try to gain access at a given time and some nodes are forced into backoff.

Since the CSMA/CA protocol is a random access scheme with backoff, it suffers from low fairness performance due to the backoff mechanism. When a sensor node fails to acquire the channel, it will double its backoff window. Under heavy loads, the fairness performance is poor as once a sensor node is able to transmit a packet it will have much better probability of getting access to the channel again than other sensor nodes who might have backoff waiting periods. On the other hand, since the VSDH-MAC performs selective backoff using the CTS SINR threshold, it reduces the number of nodes entering backoff.

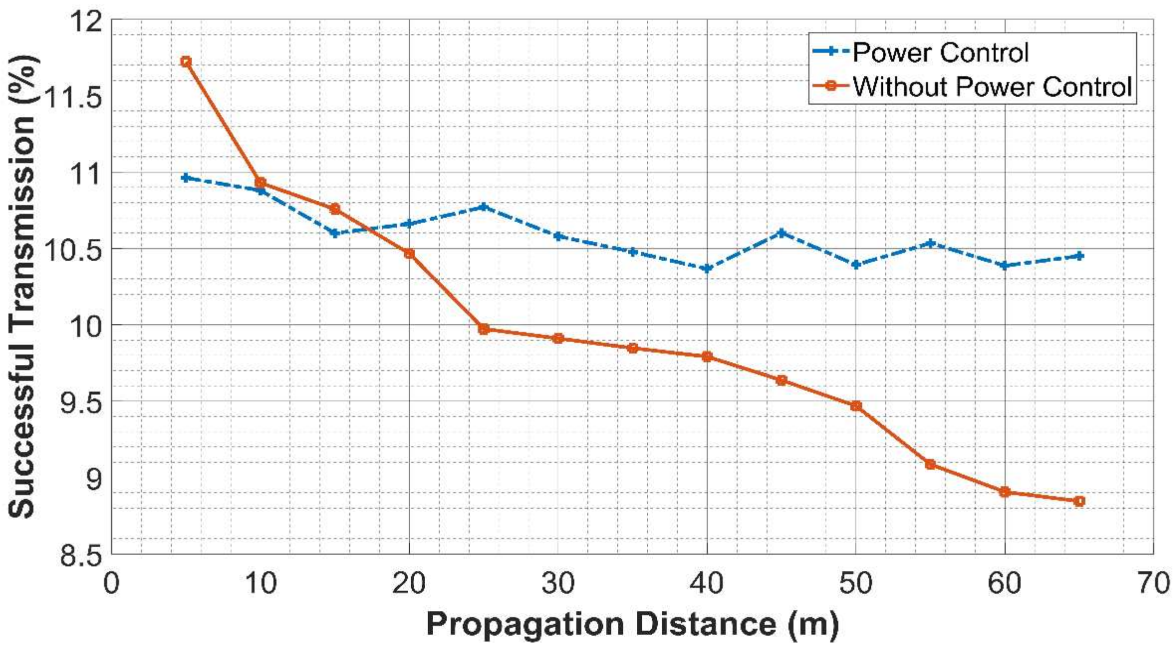

Figure 10. The proportion successful transmissions as a function of distance from the hub at maximum throughput.

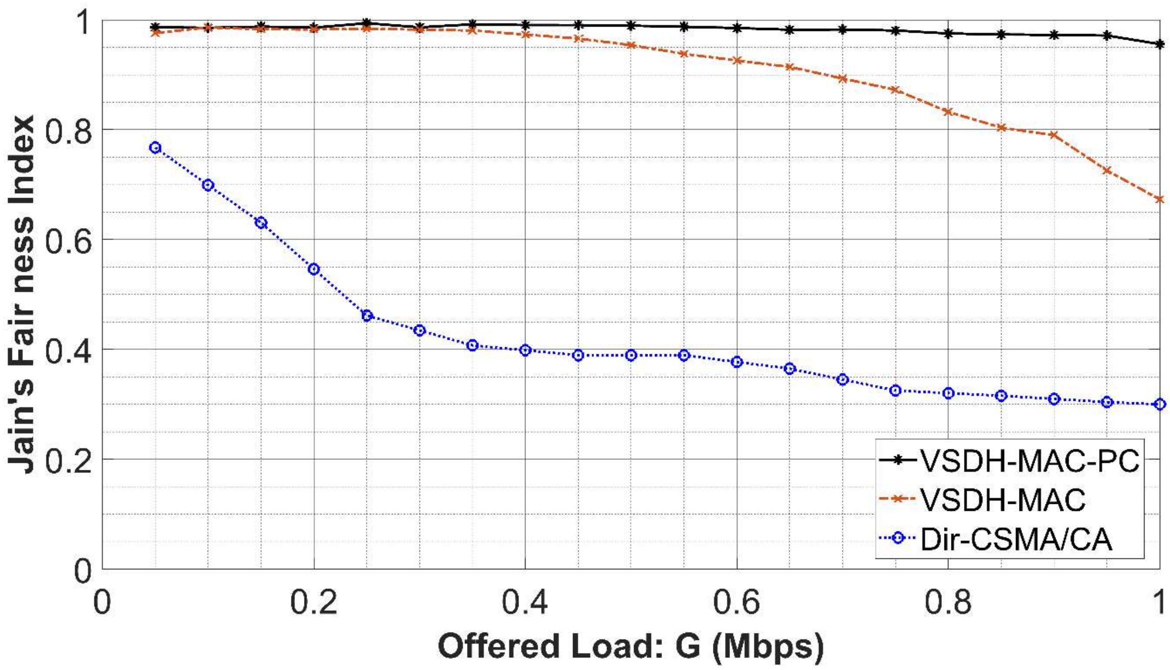

Figure 11. Jain's fairness index improvements with the power control mechanism applied compared to VSDH-MAC with no power control and the modified directional CSMA/CA in a network with 50 nodes.

Figure 12 shows the relationship between throughput and number of nodes within the network. As the number of nodes in the network increases, the collisions of RTS at the hub increase, sending more nodes into NAV (backoff) hence reducing the throughput. However, as the number of nodes approach a certain threshold, the network throughput levels off to a near constant value.

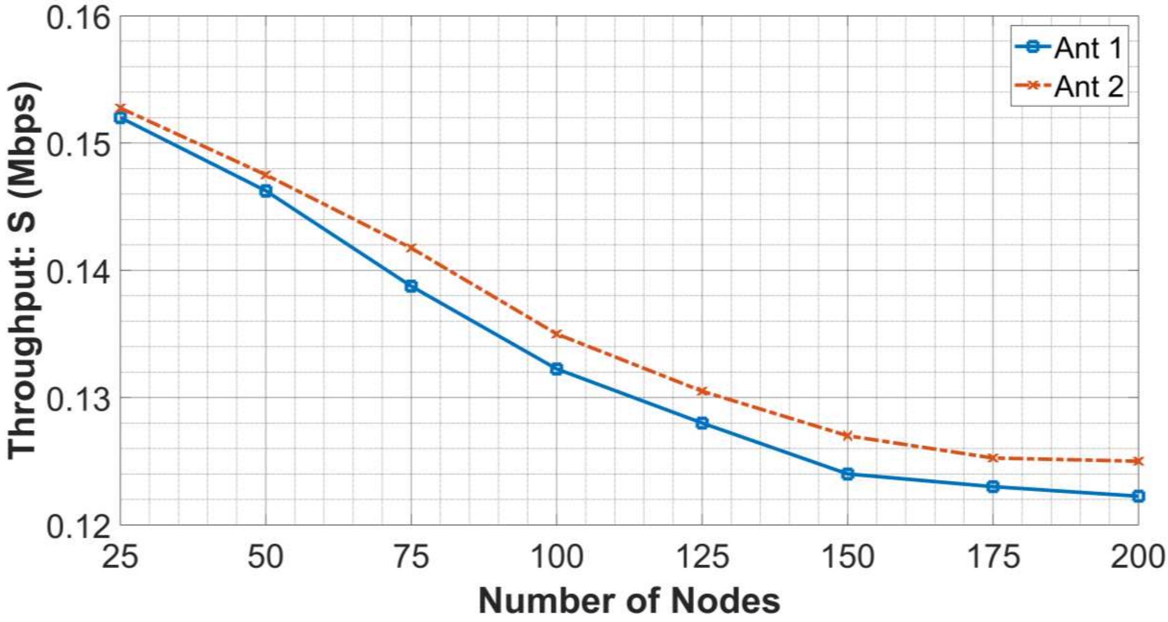

Figure 11. Impact of number of nodes on maximum throughput.

5. Conclusions

In this paper it is shown that the proposed VSDH-MAC and DIFS-VSDH-MAC protocols offer excellent performance in dealing with the trade-off between throughput and node energy consumption. The use of virtual carrier sensing provides the lowest energy consumption, but with a small increase in energy consumption the inclusion of actual carrier sensing provides almost twice the throughput. The major advantage of the VSDH-MAC and VSDH-MAC-DIFS protocols is that they exploit the potential of directional antennas and spatial reuse in achieving high overall network throughput, energy efficiency and improved fairness. It is also worth noting that contention-based protocol tends to have low latency compared to contention-free protocol under low traffic load. Simulation results have shown that the VSDH-MAC protocol is able to provide better throughput and energy efficiency performance than other directional IEEE 802.11 DCF protocols. It should also be noted that we have found the use of real, rather than ideal antenna patterns can make a substantial difference in the network performance, with ideal antennas, the throughput appears to be larger than possible with real antennas, due to the capacity reduction brought about by beam overlap.

Further work is required to consider the performance of the VSDH-MAC and DIFS-VSDH-MAC protocol for mobile WSN scenarios. Also 3-dimentional (3D) scenarios and the effects of non line of sight transmission should be considered.

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