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Chau, Arnold, Dawson, John Frederick orcid.org/0000-0003-4537-9977, Mitchell, Paul Daniel orcid.org/0000-0003-0714-2581 et al. (1 more author) (2020) Virtual sensing directional hub MAC (VSDH-MAC) protocol with power control. *Electronics*. 1219. ISSN 2079-9292

<https://doi.org/10.3390/electronics9081219>

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1 Article

2 Virtual Sensing Directional Hub MAC (VSDH-MAC) 3 Protocol with Power Control

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9 Received: date; Accepted: date; Published: date

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

22

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

25

26

27 1. Introduction

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

37 On selection of suitable MAC protocols for WSNs, one could consider either contention-based
38 or contention-free protocols. Contention-based protocols can be less efficient than those without
39 contention in terms of throughput performance for large star topologies due to the large number of
40 collisions when the data traffic offered load is high. However, they are simpler and typically provide
41 lower delay in smaller WSNs [4]. Contention-based protocols are a promising approach for

42 directional MAC protocols, as they enable multiple nodes to simultaneously access a channel without
43 the need for synchronization. Scheduling and synchronization are the main challenges for contention-
44 free protocols, especially for WSNs with mobile nodes and/or a varying number of nodes.

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

57 Most previous works on the use of directional antennas have assumed the use of idealized
58 antenna patterns where each antenna beam is distinct, with no overlap with adjacent beams and
59 having a constant antenna gain across the beam [7-15]. Some work has assumed that the nodes are
60 capable of knowing each other's position [7,9-11] or that nodes have complex, steerable antennas
61 [7,12]. Also multiple antennas are often required at the nodes as well as the hub [7-13,16] which
62 increases both the complexity and energy consumption of the nodes. Some of the protocols proposed
63 also require multiple channels to successfully operate [8,13,16]. Only a few papers within the
64 literature [14,17-19] have considered the energy consumption of the protocol, which is an important
65 factor for low power nodes [20].

66 In this paper, a modified directional CSMA/CA (carrier sense multiple access with collision
67 avoidance) protocol is proposed, which is similar to the IEEE 802.11 WI-FI standard and the IEEE
68 802.15.4 standard for WSNs. A version without the traditional physical carrier sensing is used (to
69 reduce energy consumption). Here virtual carrier sensing is performed via handshaking packets. A
70 version with physical carrier sensing similar to the CSMA/CA protocol is also considered for
71 comparison. The hub node is equipped with multiple directional antennas, and the channel is
72 efficiently utilized through the benefits of spatial reuse. A dynamic transmit power control algorithm
73 is employed at the wireless sensor nodes to improve node energy efficiency. A uniform signal-to-
74 interference-plus-noise ratio (SINR) is achieved for packets from all sensor nodes in the network. As
75 shown through simulations, the proposed protocol leads to improvements in network throughput,
76 energy consumption, and fairness performance. The effects of antenna pattern overlap are also
77 significantly reduced by the proposed protocol.

78 The rest of the paper is organized as follows: In Section 2 we describe the network topology and
79 proposed MAC protocol in detail. In Section 3 we describe the simulation methodology and in section
80 4 we present results that show the improved throughput and performance that can be achieved, along
81 with the effect of the antenna gain, power control algorithm, and antenna pattern.

82 2. Medium Access Control Protocol

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

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

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

100 2.1 VSDH-MAC Channel Access Algorithm

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

141 Operation of the protocol at the hub is slightly more complex as it has multiple antennas and
142 corresponding transceivers. The hub algorithm differs in the following manner. It is assumed to be

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

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

163

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.

```

1  for each packet arriving queue do
2    while  $cd\_CW = 0$  do
3      if ongoing transmission = 0 then
4        Send RTS to receiver
5        Start countdown timer ( $cd\_RTS$ )
6        if CTS received &&  $cd\_RTS > 0$  then
7          update  $P\_tx$  based on the CTS received power
8          Send DATA to receiver
9          Start countdown timer ( $cd\_DATA$ )
10         if ACK received &&  $cd\_DATA > 0$  then
11           Packet transmission successful
12         else
13           Update  $P\_tx$  to maximum
14         else if CTS for other nodes received &&  $cd\_RTS > 0$  then
15           Update  $cd\_NAV$  based on overhead CTS
16            $cd\_CW =$  a random CW value (where  $CW = [0, CW\_max - 1]$ )
17           Start countdown timer ( $cd\_CW = cd\_NAV + cd\_CW$ )
18         else
19           Update  $P\_tx$  to maximum
20            $cd\_CW =$  a random CW value (where  $CW = [0, CW\_max - 1]$ )
21           Start countdown timer ( $cd\_CW$ )

```

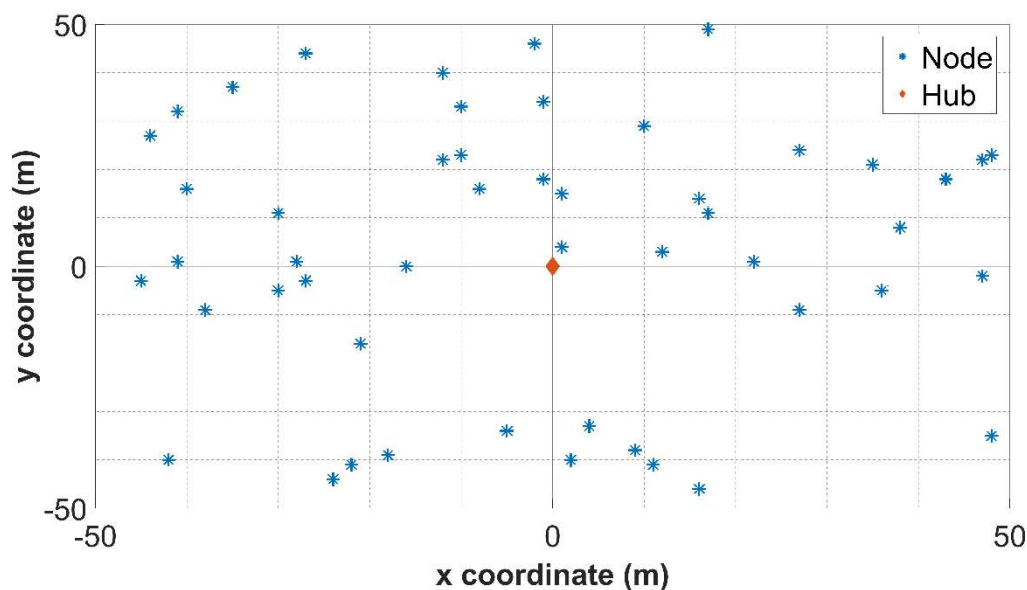
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165

166 3. Simulation Methodology

167 3.1. Network Configuration

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



179

180 Figure 1. An example of centralized WSNs topology.

181 3.2. Simulation Setup

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

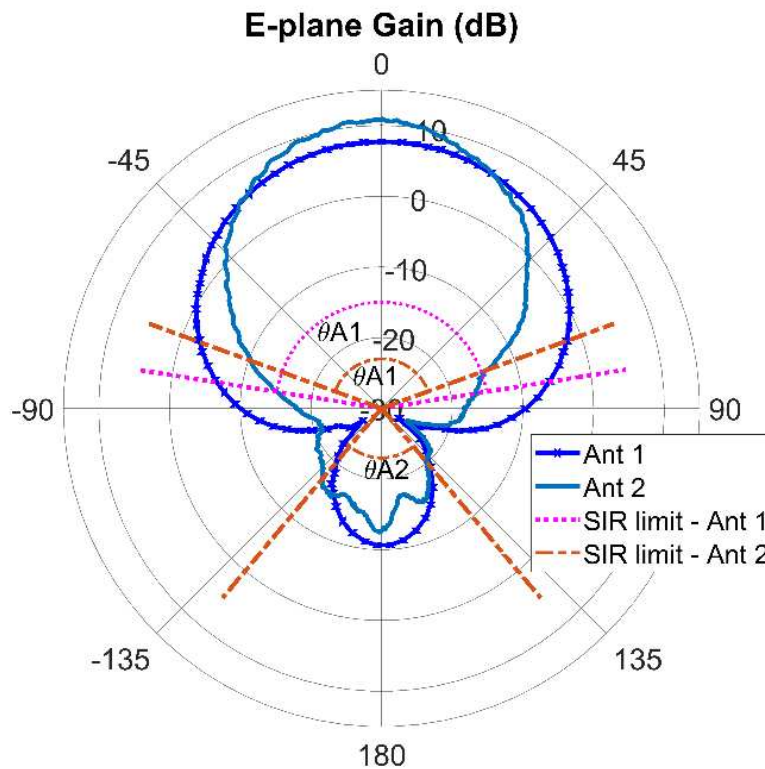
193 The transmission parameters are shown in Table 1. Note that SIFS and BPSK, in Table 1 stand
194 for Short Interframe Space and Binary Phase Shift Keying, respectively. The simulator uses the SINR
195 to determine the bit error rate (BER). This BER value is used to determine if each individual bit is
196 received in error, assuming randomly distributed errors. A uniformly distributed random number
197 between zero and one is generated randomly. This number is compared with the BER threshold
198 (obtained from a look up table of SINR vs BER for a given modulation scheme), and one or more bit

199 errors will result in a discarded packet. Packets with errors are rejected by the protocol. The data
 200 packets are generated according to a Poisson process with a rate (G), which is referred as the channel
 201 offered load or traffic load. The Poisson arrival process gives an exponentially distributed inter-
 202 arrival time of the data packet generation.

203 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

204



205

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

208 3.3. Directional Antennas

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

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

214 3.4. Energy Consumption Calculation

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

218 Successful data packet transmission (E_{tx}):

219

$$E_{tx} = P_{tx_{RTS}} T_{RTS} + P_{tx_{DATA}} T_{DATA} + P_{rx} (T_{CTS} + T_{ACK} + 2 \times (T_p + T_{SIFS})), \quad (1)$$

220

221 Colliding RTS or CTS transmission ($E_{c_{RTS}}$):

222

$$E_{c_{RTS}} = P_{tx_{RTS}} T_{RTS} + P_{rx} (T_{CTS} + T_p), \quad (2)$$

223

224 Colliding DATA or ACK transmission ($E_{c_{DATA}}$):

225

$$E_{c_{DATA}} = E_{c_{RTS}} + P_{tx_{DATA}} T_{DATA} + P_{rx} (T_{ACK} + T_p + T_{SIFS}), \quad (3)$$

226

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

228

$$E_{BO} = E_{c_{RTS}} + P_{sleep} (T_{CW}), \quad (4)$$

229

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

231

$$E_{OH} = E_{c_{RTS}} + P_{rx} (T_{SIFS}) + P_{sleep} (T_{NAV} + T_{CW}), \quad (5)$$

232

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

234

$$E_{sleep} = P_{sleep} T_{sleep}, \quad (6)$$

235

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

237

$$E_{DIFS} = P_{rx} T_{DIFS}, \quad (7)$$

238

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

242

$$E_{OH_DIFS} = E_{DIFS} + P_{sleep} (T_{NAV} + T_{CW}), \quad (8)$$

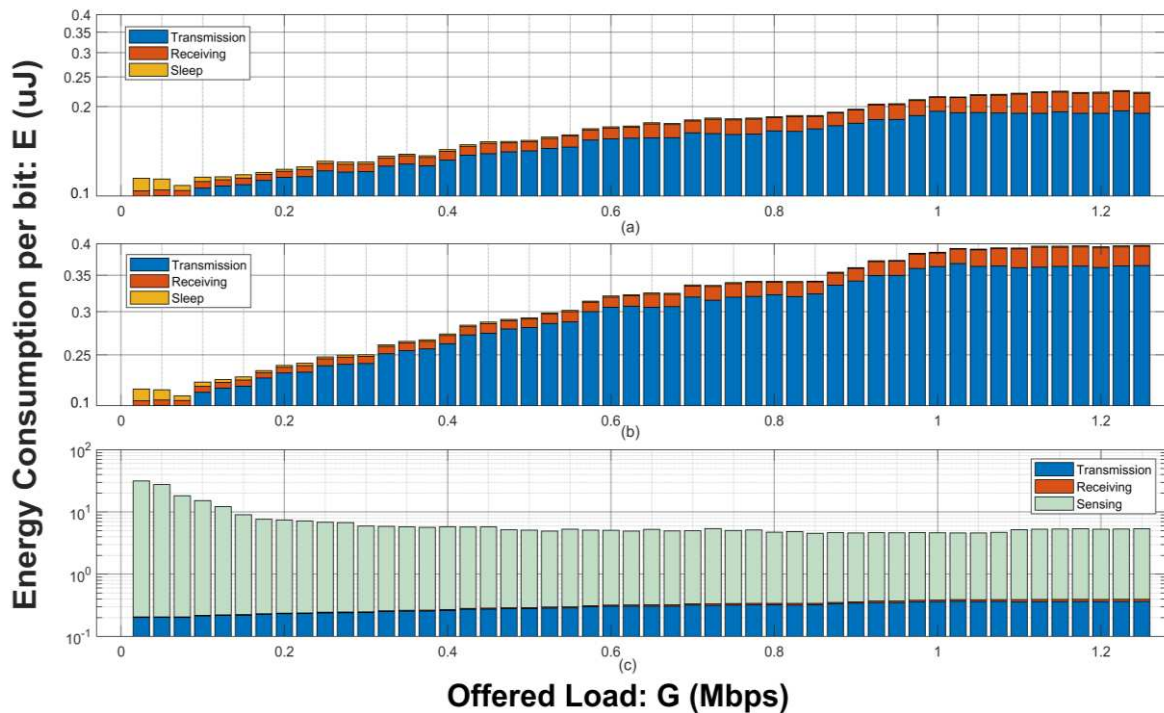
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244 where, P_{sleep} , $P_{tx_{RTS}}$, $P_{tx_{DATA}}$ and P_{rx} are the power consumed in sleep, transmit and receive mode
245 respectively. T_{SIFS} , T_{DIFS} and T_p are the SIFS and DIFS time duration from IEEE 802.11 DCF standard
246 and the propagation time of the packet. T_{CW} is the backoff time duration. T_{RTS} , T_{CTS} , T_{DATA} , and T_{ACK}
247 denotes the packet transmission time for RTS, CTS, DATA, and ACK packets respectively. T_{sleep} is

248 the time for the node to stay in the sleep state. T_{NAV} represents the backoff time indicated from the
 249 received NAV.

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

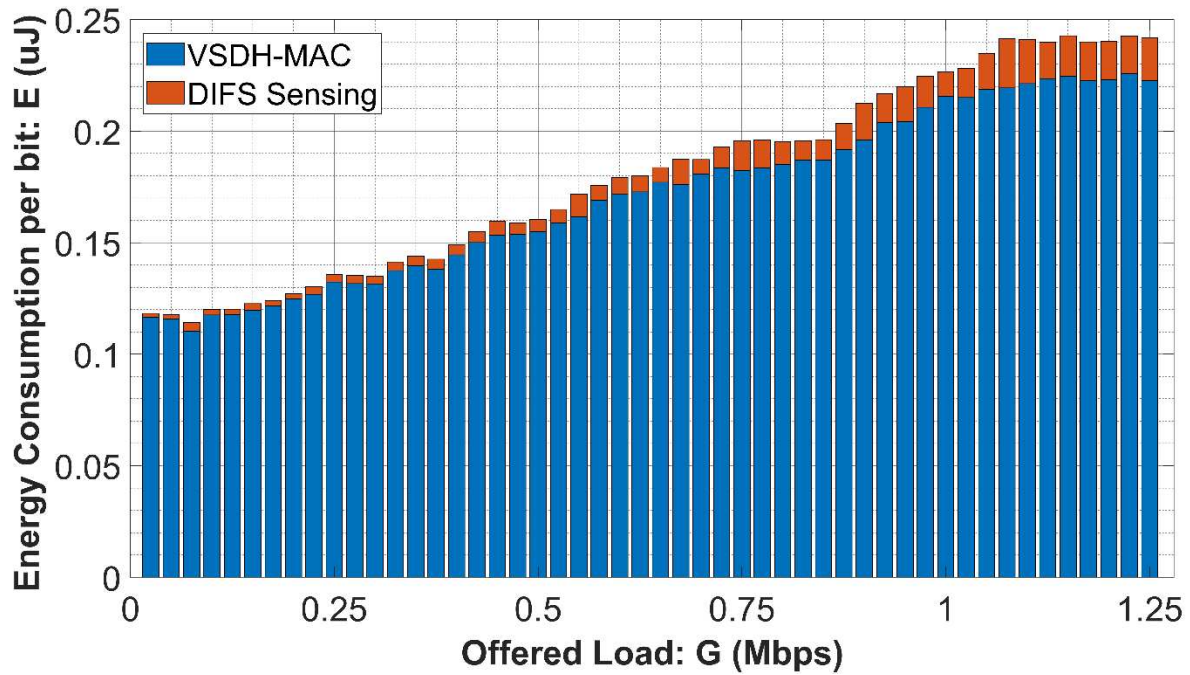
259 We expect the number of hub antennas to have a small impact on the node energy usage in a given
 260 scenario. Firstly, as the number of nodes in each sector is reduced there is likely to be fewer collisions
 261 which would reduce the energy wasted by this mechanism. Also an increased number of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



264

265
 266

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).



267

268

269

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

270

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)

271

272 4. Results Analysis

273

274

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277

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 M Erlangs, in which 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.

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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 that 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.

287

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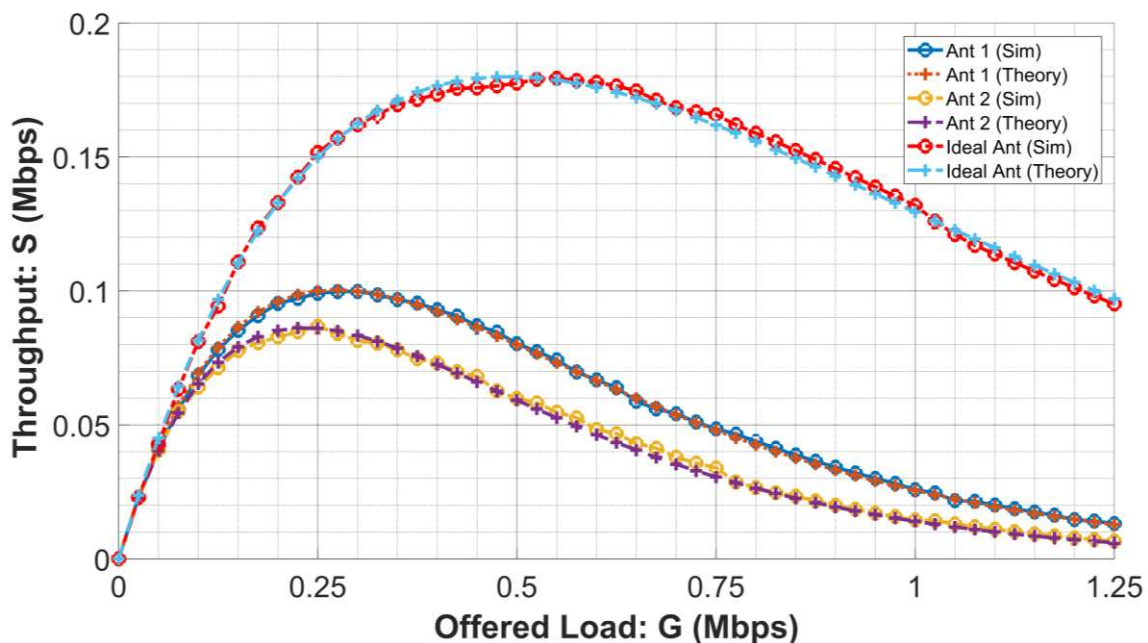
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291

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.

292 It is useful to compare the throughput performance of the VSDH-MAC and DIFS-VSDH-MAC
 293 protocols with other directional MAC protocols. Two other directional MAC protocols have been
 294 replicated for the purpose of performance comparison. Both protocols have been replicated with the
 295 parameters described in section 3. In the DMAC (Directional Virtual Carrier Sensing MAC) protocol
 296 proposed in [24], the simulation results showed a saturation throughput of 0.225 Mbps with the same
 297 simulation setup as in Section 3. However, it is assumed that all nodes are equipped with
 298 beamforming directional antennas and Global Positioning System (GPS). The DMAC protocol is
 299 based on the IEEE 802.11 standard and nodes are required to perform channel sensing prior to
 300 transmission. The use of GPS and channel sensing has significantly increased the node energy
 301 consumption. With idealized antenna patterns, the VSDH-MAC and DIFS-VSDH-MAC protocols can
 302 achieve a saturated throughput of 0.336 Mbps and 0.426 Mbps, which is approximately a factor of 1.5
 303 or 1.9 higher than the saturated throughput of DMAC. The CMDMAC (Cooperative Multichannel
 304 Directional MAC) is a similar protocol that requires multiple channels [25]. It requires one radio
 305 channel for control packets such as RTS, CTS and ACK, and a second radio channel for data
 306 transmission. Our simulation results indicate a saturated throughput of 0.45 Mbps from the
 307 CMDMAC protocol with the same simulation setup as in Section III and ideal directional antennas.
 308 All sensor nodes must be equipped with an omni-directional antenna for overhead communication
 309 and an idealized steerable directional antenna for data transmission. The additional channel provides
 310 continuous channel sensing which provides advantages in terms of throughput performance.
 311 Although the CMDMAC protocol provides better throughput performance compared with the
 312 VSDH-MAC protocol, under these conditions, the additional requirements mean that the throughput
 313 performance comes at the cost of increased node manufacturing cost and energy consumption.
 314 Moreover Figure 7 shows that the throughput performance of applying an idealized antenna pattern
 315 is significantly higher than using realistic antenna patterns.
 316

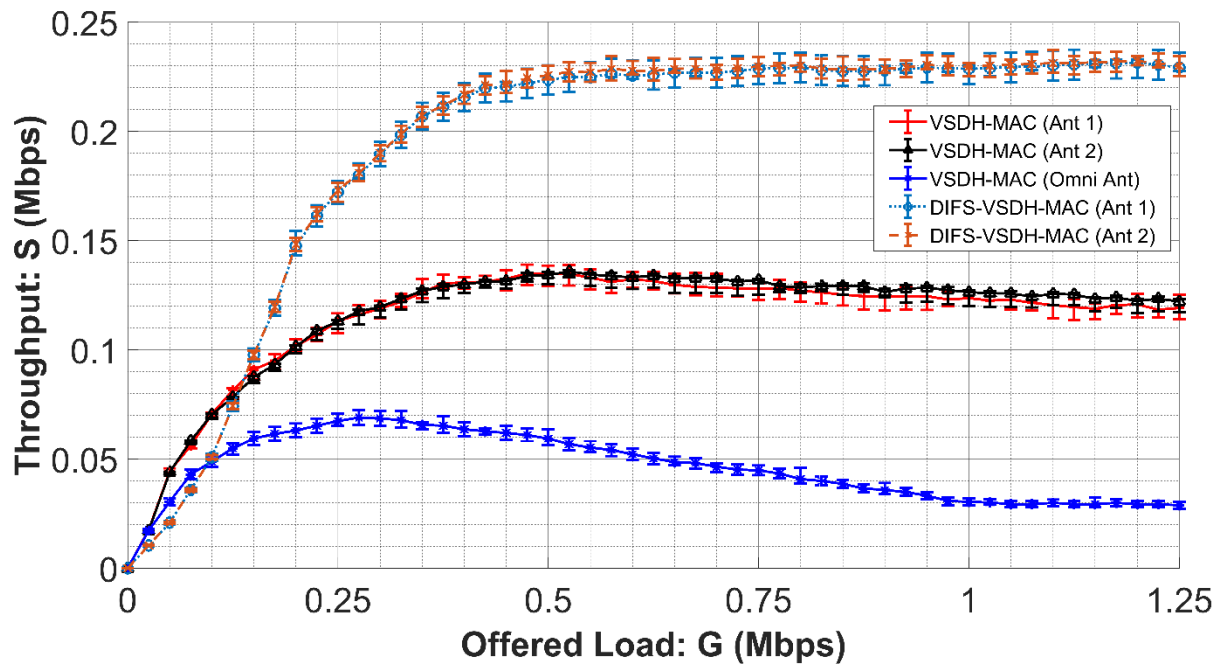


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318 Figure 5. Throughput comparison of different antenna patterns with the DH-Aloha protocol with
 319 $M = 4$.

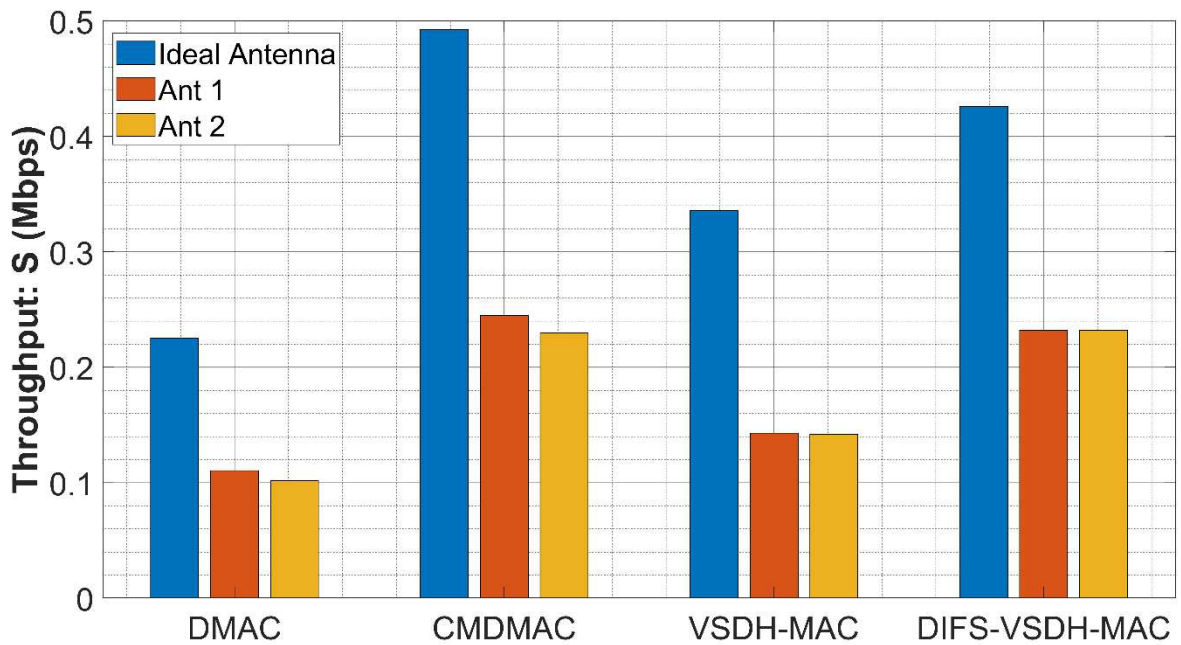
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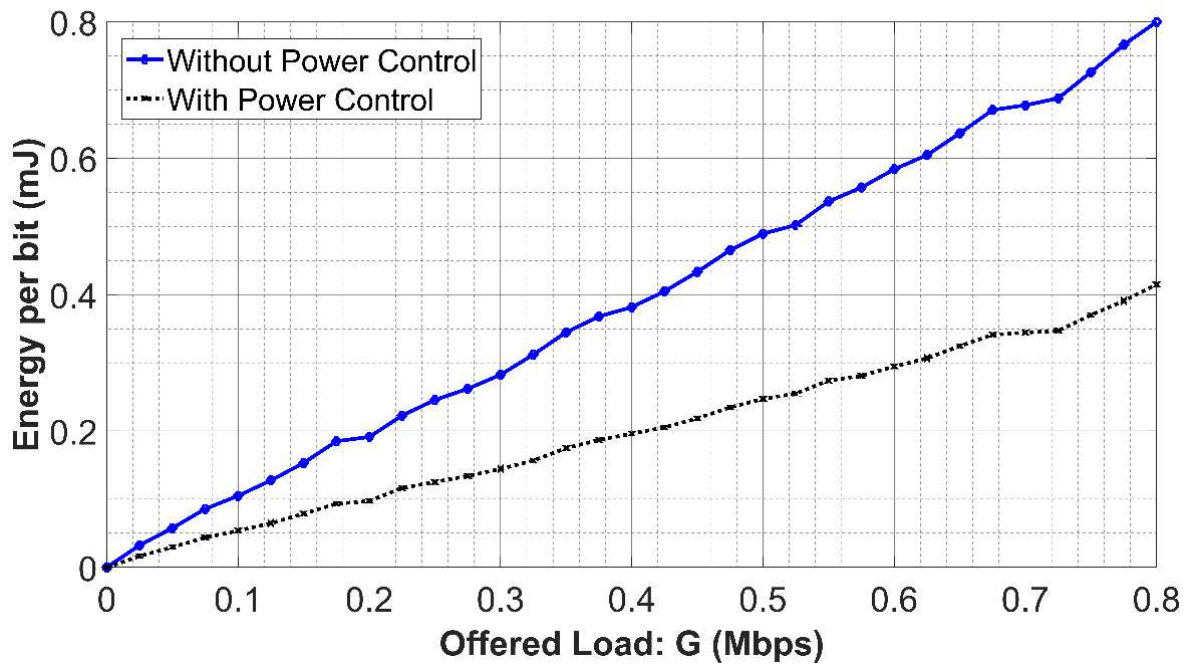
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Figure 6. Throughput of the VSDH-MAC and DIFS-VSDH-MAC protocols with different antennas patterns with $M = 4$, compared against the VSDH-MAC with a single omni-directional hub antenna.



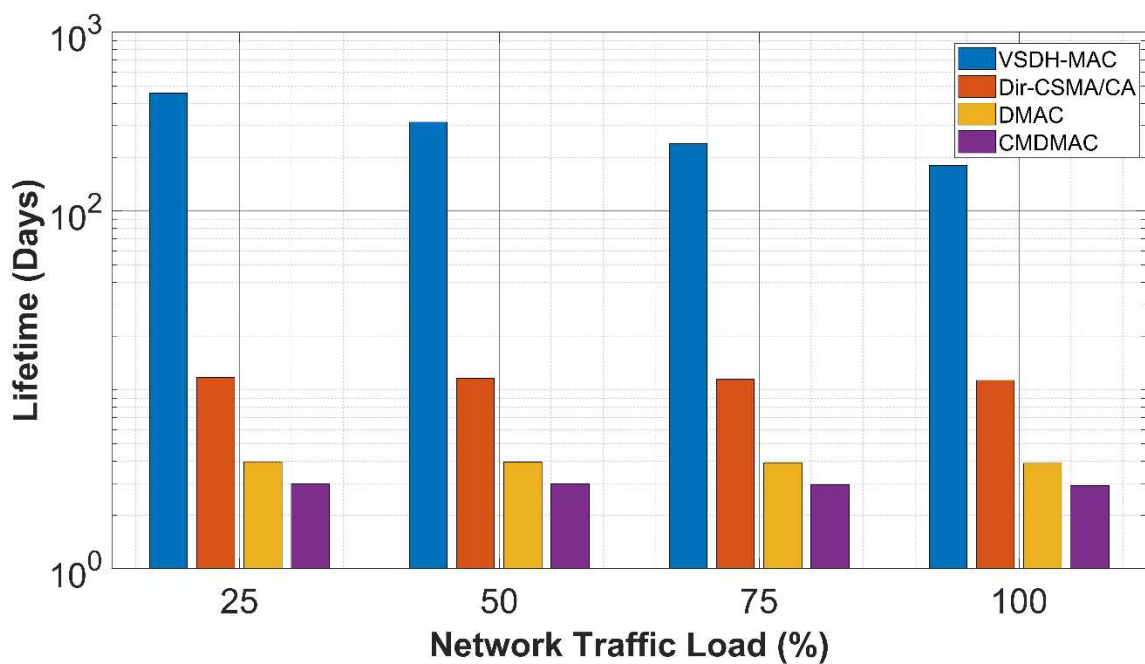
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Figure 7. Impact of antenna pattern on throughput performance with $M = 4$.



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



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

337 Figure 8 shows the average transmission energy required by the VSDH-MAC protocol with and
338 without power control, for each successful data bit. The power control algorithm can reduce the
339 average required transmission energy by a factor of 2. One of the goals of the VSDH-MAC is to
340 prolong the lifetime of the sensor and hence the network lifetime. To quantitatively compare these
341 directional MAC protocols, we adopt the quoted values of current consumption values from MICAz
342 mote [26]. Two 1.5V batteries rated at 2000 mAh each are assumed for each sensor node. We assume

343 the current draw and the size of the packets are fixed. Figure 9 shows the numerical comparison of
 344 the expected lifetime obtained from the directional MAC protocols including the directional
 345 CSMA/CA. Figure 8 and 9 highlights that the energy efficiency and lifetime expectancy of the VSDH-
 346 MAC outperforms the other protocols. Comparing to the VSDH-MAC protocol, the physical carrier
 347 sensing from the other directional MAC protocols contribute a significant amount of energy
 348 consumption to the sensor nodes. This mechanism with the lack of transmit power control further
 349 reduce the lifetime of the sensor nodes. It is important to have an accurate energy model and lifetime
 350 estimation of a sensor node, as it directly impacts the lifetime of a WSN.

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

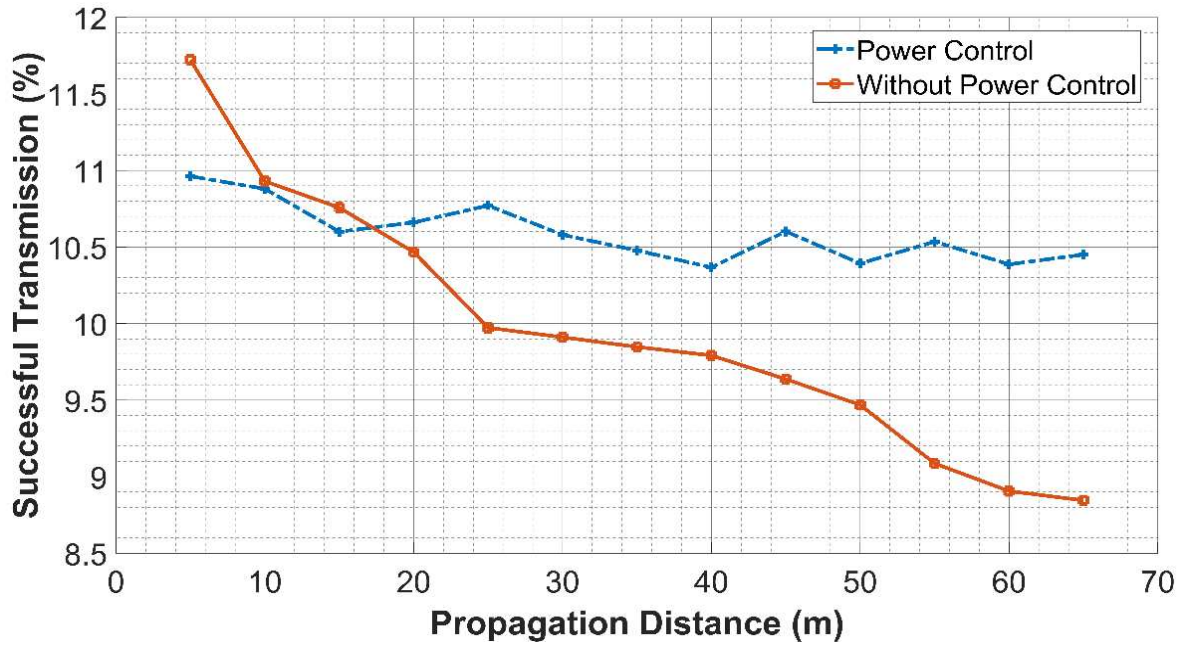
358 Figure 11 compares the fairness performance of VSDH-MAC protocol and IEEE 802.11 DCF
 359 using Jain's fairness index [27]. Jain's fairness index is used to determine the fairness of the network
 360 at different offered loads, and is defined by:
 361

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

362 where n is the number of nodes in the network, x_i is the throughput of the i^{th} node within the
 363 network. The fairness index ranges from $\frac{1}{n}$ to 1. Ideally, when all sensor nodes share the channel
 364 equitably, the fairness index should be equal to 1.
 365

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

372 Since the CSMA/CA protocol is a random access scheme with backoff, it suffers from low
 373 fairness performance due to the backoff mechanism. When a sensor node fails to acquire the channel,
 374 it will double its backoff window. Under heavy loads, the fairness performance is poor as once a
 375 sensor node is able to transmit a packet it will have much better probability of getting access to the
 376 channel again than other sensor nodes who might have backoff waiting periods. On the other hand,
 377 since the VSDH-MAC performs selective backoff using the CTS SINR threshold, it reduces the
 378 number of nodes entering backoff.
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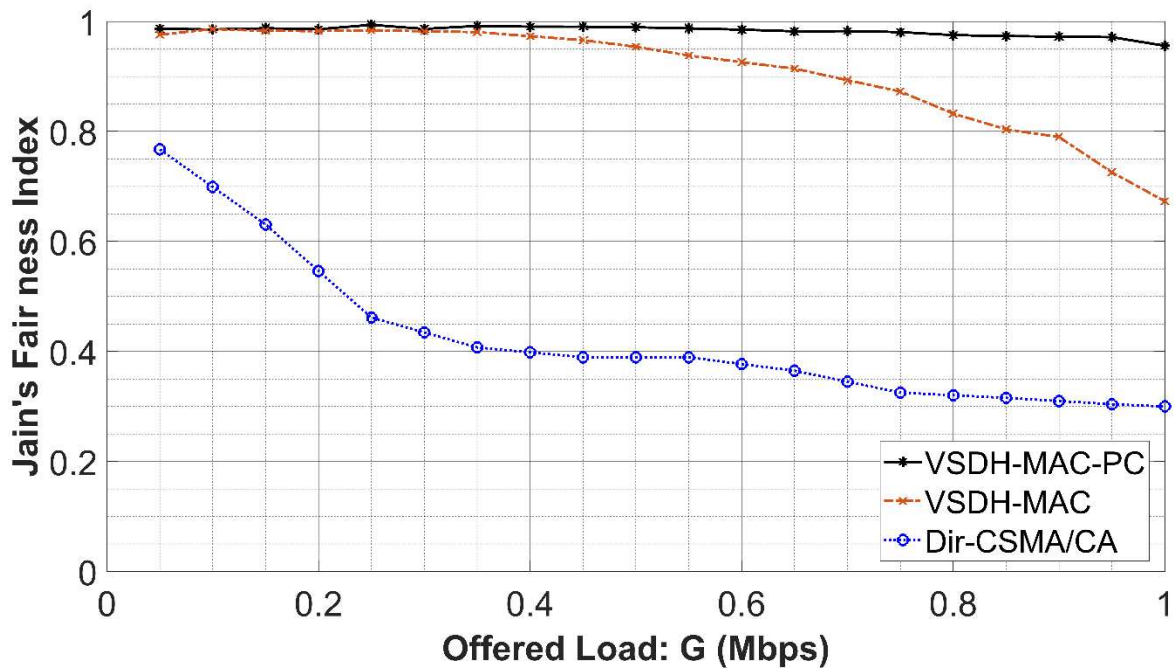
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Figure 10. The proportion successful transmissions as a function of distance from the hub at maximum throughput.

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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.

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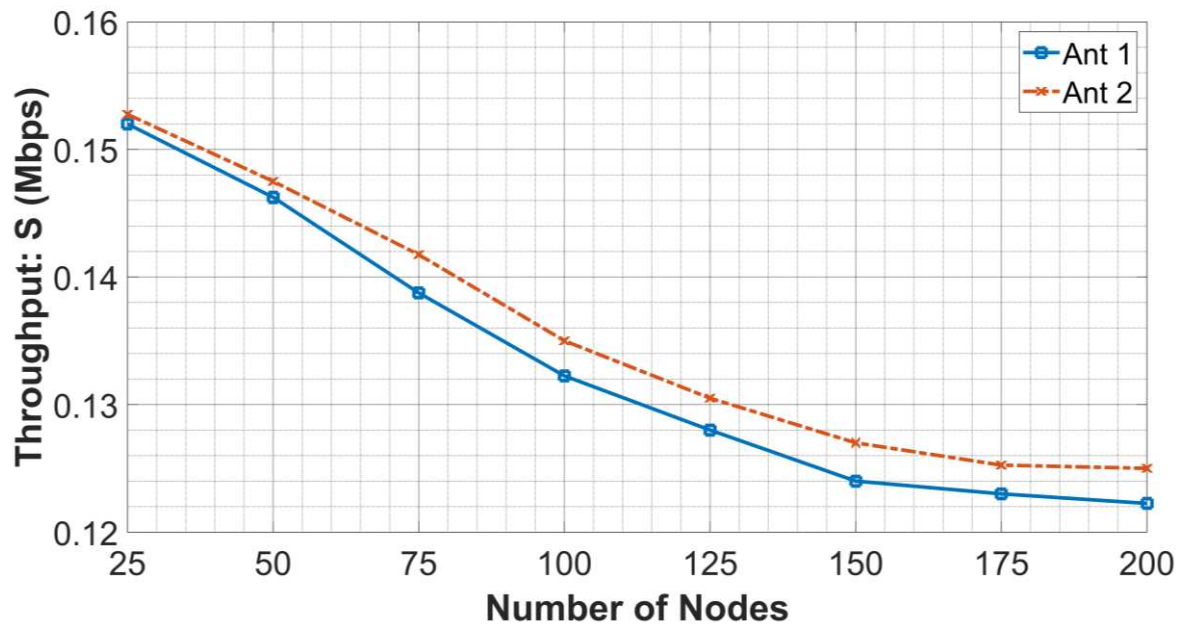
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Figure 12 shows the relationship between throughput and number of nodes within the network. As the number of nodes in the network increases, the collisions of RTS at the hub increase, sending more nodes into NAV (backoff) hence reducing the throughput.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

394



395

396

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

397

398 5. Conclusions

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

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

415

416 Author Contributions: Conceptualization, Arnold Chau, John Dawson, Paul Mitchell and Tian Loh; Data
 417 curation, Arnold Chau; Formal analysis, Arnold Chau, John Dawson and Paul Mitchell; Methodology, Arnold
 418 Chau, John Dawson, Paul Mitchell and Tian Loh; Software, Arnold Chau and Paul Mitchell; Validation, Arnold
 419 Chau; Writing – original draft, Arnold Chau, John Dawson and Paul Mitchell; Writing – review & editing, Arnold
 420 Chau, John Dawson, Paul Mitchell and Tian Loh.

421

422 **Funding:** This research received no external funding.

423

424 **Conflicts of Interest:** The authors declare no conflict of interest.
425

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