Using Directional Transmissions and Receptions to Reduce Contention in Wireless Sensor Networks

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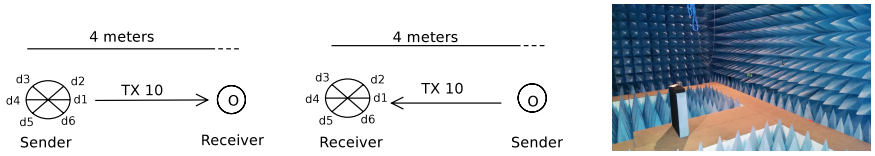
Abstract. Electronically Switched Directional (ESD) antennas allow software-based control of the direction of maximum antenna gain. ESD antennas are feasible for wireless sensor network. Existing studies with these antennas focus only on controllable directional *transmissions*. These studies demonstrate reduced contention and increased range of communication with no energy penalty. Unlike existing literature, in this paper we experimentally explore controllable antenna directionality at both sender *and* receiver. One key outcome of our experiments is that directional transmissions and receptions together considerably reduce channel contention. As a result, we can significantly reduce intra-path interference.

1 Introduction

Electronically switched directional (ESD) antennas allow software-based control of the direction of the maximum antenna gain. ESD antennas bring spatial diversity to wireless applications, and have been shown feasible for real world sensor networks. Previous work has studied the impact of introducing controllable directionality at the sender nodes only. These studies demonstrate improvements in network performance because of reduced contention [1] and increased range of communication [2, 3]. There is, however, no experimental evidence about performance improvements brought by introducing controllable antenna directionality at both sending and receiving nodes.

Directional transmissions alleviate contention by conveying radiated power in the intended direction of communication. Nevertheless, antennas are reciprocal in nature, *i.e.*, they have similar receiving and sending patterns [4]. This suggests directional receptions enabled by these antennas could, for example, help alleviate channel contention from nearby nodes. Increased contention for the channel leads to higher packet loss, increased latency, and decreased throughput resulting in decreased lifetime of sensor network applications. Introducing directional reception could further alleviate contention by attenuating the signal at the receivers from nodes in unintended directions of communication.



(a) Sending pattern experiment. (b) Receiving pattern experiment. (c) Experiment setup in anechoic chamber

Fig. 1: Experimental setup used to demonstrate similar sending and receiving pattern of SPIDA antennas. d1-d6 indicate possible SPIDA directions. d7 indicates omni-directional configuration. O indicates a probe node with omni-directional antenna.

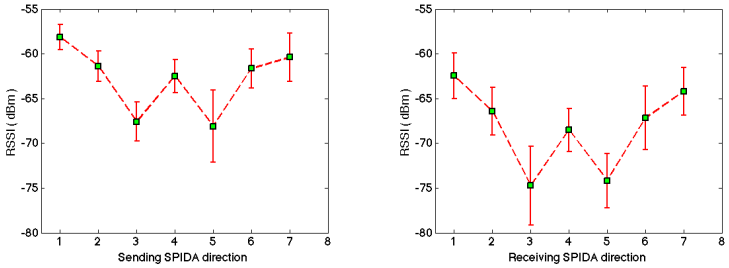
We build a number of SPIDA ESD antennas [2] for our experiments in this paper. We evaluate these antennas as receivers and observe similarity in sending and receiving patterns. We experiment with these antennas arranged in a rectangular grid and a linear chain of nodes. Our experiments confirm that directional transmissions and receptions reduce channel contention. Our experiments also suggest that we can significantly reduce intra-path interference in linear networks, a problem experienced in high-throughput protocols such as Flush [5] and PIP [6]. Finally, we demonstrate that by exploiting directional transmissions and receptions and the capture effect, simultaneous communication flows between multiple sender-receiver on one wireless channel only are possible. In contrast to other protocols such as Strawman [7] that reduces the contention by distributing transmissions in time, our approach tackles the problem in space.

The key contribution of this paper is to confirm that directional transmission and reception together indeed significantly reduce channel contention and intra-path interference. The rest of the paper unfolds as follows: Section 2 provides a brief background on ESD antennas and verifies that the prototypes we build exhibit a directional behavior. In Section 3 we report on our experiments demonstrating how exploiting directional transmissions and receptions can reduce contention and intra-path interference. Section 4 places our results in perspective against existing literature and concludes the paper.

2 Electronically Steerable Directional Antennas

The SICS Parasitic Interference Directional Antenna (SPIDA) is based on the concept of *Electrically-Switched Parasitic Element*. Nilsson designed SPIDA for low powered wireless-sensor networks [2]. SPIDA has six parasitic elements surrounding a quarter wavelength monopole antenna. The parasitic elements can be individually grounded or isolated. When all parasitic elements are isolated, the antenna is configured in omni-directional mode. When all elements are grounded except one, the direction of maximum antenna gain points towards the direction of the isolated element. Encouraged by results obtained with the SPIDA antenna [1, 2, 8], we construct and use SPIDA antennas for our experiments.

We evaluate the antenna prototypes we build in terms of the ability to control the direction of maximum antenna gain. We further evaluate the receiving be-



(a) Sending pattern (b) Receiving pattern

Fig. 2: Mean RSSI using SPIDA antenna as sender and as a receiver. Changing direction of maximum gain has significant effect on RSSI. *The receiving pattern looks very similar to the sending radiation pattern suggesting reciprocity.*

haviour and sending behaviour of SPIDA antennas to show reciprocity in sending and receiving patterns of SPIDA antennas.

Our experimental setup consists of Tmote sky nodes equipped with the antennas as shown in Figure 1. We perform the experiment in an anechoic chamber to reduce the effect of multi-path and external interference. As a sender, the SPIDA-equipped node is configured to broadcast packets containing the sending direction, sequence number, and transmit power at an inter-packet interval (IPI) of $\frac{1}{2}$ second. Even though we are in an anechoic chamber, we chose this IPI since it usually prevents successive packet loss due to link burstiness [9] and our experiments in the next section are not performed in the chamber. We reconfigure the direction of the maximum antenna gain in a round robin manner sending ten packets in one direction before switching direction. When receiving a packet the probe node logs RSSI, antenna configuration, sequence number and node id onto onboard flash. In the second experiment we observe the receiving pattern. The roles of the SPIDA-equipped node and probes are reversed, keeping all other parameters the same. The node equipped with the omnidirectional antenna broadcasts beacon messages. The receiver with the SPIDA antenna stores RSSI, receiving direction, and sequence number onto onboard flash.

Figure 2 shows the result of our experiments. The figure depicts the mean RSSI of the received packets for five different SPIDA antennas used as sender and as receiver in the first and second type of experiment, respectively. The error bars show the standard deviation across the antenna prototypes. The graph shows that we can control the direction of the maximum antenna gain with the received signal strength being the highest when the antenna is configured in the direction of node 1. Configuring the direction of the maximum antenna gain away from the node leads to a decrease in signal strength of the received packets, with direction 3 and 5 being the worst performing directions. This is consistent with earlier results [8]. The more interesting result is the large difference in signal strength between the best direction (direction 1) and the worst direction (direction 3). We also observe as expected, a close resemblance in the sending and receiving patterns of the SPIDA antenna, which demonstrates the antenna's reciprocity.

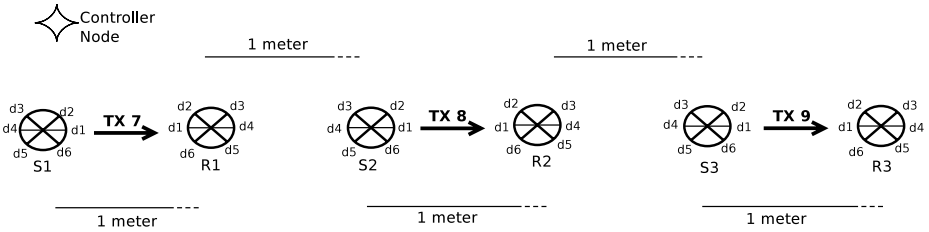


Fig. 3: Experimental setup for linear communication. Arrow directions denote the paired nodes. TX7,TX8,TX9 indicate the senders' output power.

3 Experimental Evaluation

In this section, we show that directional transmissions and receptions reduce channel contention. We also show that this allows nodes in a linear network to communicate simultaneously on the same wireless channel.

3.1 Basic Experimental Setup

We arrange the nodes according to Fig. 3 and Fig. 4, for two topologies that we call rectangular and linear. These topologies allow us to exploit directionality at the sender and the receiver. The nodes are arranged with direction 1 of the sender pointing towards direction 1 of the receiver antenna in line of sight. Henceforth, configuring SPIDA antenna to directional mode means that we configure the direction of the maximum antenna gain towards direction 1.

A sensor node with an omnidirectional antenna broadcasts beacon messages at transmit power TX 31 (approximately 0 dBm). We use a higher transmit power to ensure that beacon messages are received by all intended receivers independent of their antenna configuration. When receiving a beacon message, the sender and receiver nodes configure the direction of the maximum antenna gain to directional or omnidirectional mode. As the experiments are performed indoors, with nodes separated by a few meters, we use the lower transmit power TX7 to TX9 for sender nodes. We use the same transmit power for all nodes in the rectangular topology. In the linear topology nodes have incrementally higher transmit power settings according to their placement in the chain. This is required due to the short distances between the nodes in the chain and not needed when the distances between them are larger. Again, we set the inter packet interval to $\frac{1}{2}$ second to prevent successive packet losses due to link burstiness. To prevent interference from IEEE 802.11 networks, we use the IEEE 802.15.4 channel 26 in our experiments.

3.2 Alleviating Channel Contention

We investigate if directional transmissions and receptions can alleviate channel contention. We establish communication between paired nodes, *i.e.*, S1-R1, S2-R2 and S3-R3 (linear topology only). Our goal is to show that we can alleviate contention from unpaired nodes.

The nodes are arranged as discussed in the previous section. The sender nodes broadcast packets with sender node id and antenna configuration after receiving the beacon message. In these experiments we introduce a delay before we trigger the senders' broadcasts to prevent collisions of packets from different sender nodes. The receiver node logs RSSI, sender node id, as well as sending and receiving antenna configuration onto the onboard flash. In the experiments we collect roughly 7000 packets.

Fig. 5 shows the results of the experiment with nodes arranged in the rectangular grid, Fig. 6 with nodes arranged linearly. In the graphs, we plot the mean received RSSI of packets for the different antenna configurations. When nodes are arranged in the rectangular grid the RSSI of packets sent by the unpaired node is the highest. This is because of the proximity of the unpaired node and the omnidirectional configuration. However, as sender and receiver are configured to directional mode, the RSSI of packets sent by the unpaired node is reduced. The graphs shows that configuring only the sender or the receiver to directional mode has significantly less effect than configuring both to directional mode. We see a 21 dB (Fig. 5(a)) and a 15.6 dB (Fig. 5(b)) difference in RSSI for packets sent by the unpaired node between omnidirectional and directional configuration. In directional mode the RSSI of packets sent by the paired sender is the highest confirming that directionality at both sender and receiver is key to alleviate channel contention.

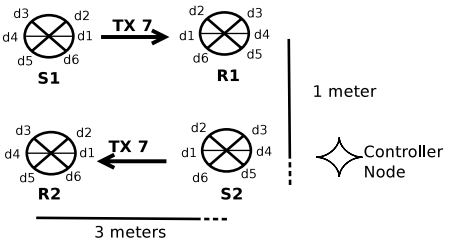
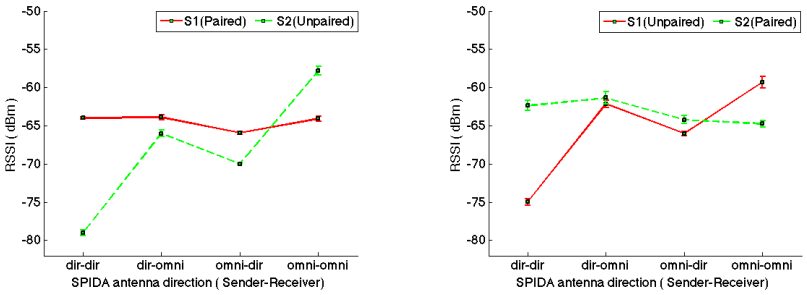


Fig. 4: Experimental setup for investigating channel contention. Nodes are arranged in a rectangular topology. S indicates sender and R receiver node.

Similar to the experiment with the rectangular topology, we expect directional transmissions and receptions to alleviate contention when nodes are arranged in the linear topology as shown in Fig. 3. Further, we expect that configuring directionality should attenuate signals from S2 and S3 for receiver node R1, and from S3 for node R2. We do not expect directional transmissions and receptions to alleviate contention for receiver node R3, as the direction of communication of S3 is the same as of S1 and S2. Also, transmissions from S2 interfere with transmissions from S1 at R1. Similarly S3 interferes with transmissions from S2 at R2. This interference is similar to intra-path interference [10].

Fig. 6(a) depicts the RSSI for packets received from different sender nodes at receiver node R1. The graph shows that in omnidirectional mode the RSSI for packets from S2 is the highest since S2 transmits at higher transmit power. As we put both sender and receiver nodes to directional configuration, we are able to attenuate the RSSI of the packets R1 receives from both S2 and S3 significantly, with the maximum effect when both sender and receiver are configured to directional mode. We observe 16.8 dB and 14.7 dB difference in RSSI of packets sent by S2 and S3 in omnidirectional and directional configuration.



(a) Node 1 (R1) (b) Node 2 (R2)

Fig. 5: Mean received RSSI of packets for the antenna configuration on the X-axis. Nodes are arranged in a rectangular grid.*Introducing directionality reduces the RSSI from the nearby unpaired node.*

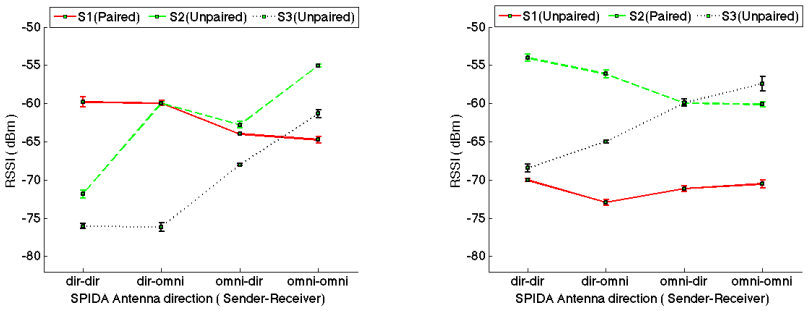
In the directional configuration, the RSSI of the paired sender is higher. The similar behaviour can be seen for node R2. The graphs shows an 11 dB difference in RSSI for packets sent by S3. This confirms our finding that directional transmissions and receptions together significantly alleviate channel contention, and suggests that intra-path interference could be significantly reduced with directional transmissions and receptions.

3.3 Simultaneous Communication Flows

In this section, we build upon the results obtained in previous section and show that directional transmissions and receptions make it possible to establish communication flows between nodes on the same wireless channel. We demonstrate this by forcing simultaneous communication between paired nodes on the same wireless channel in the following experiments exploiting the capture effect[11].

The experimental setup is similar to the one in the previous section. To allow packets from different sender nodes to collide, we remove the delay introduced after the reception of the beacon message that triggers the sender to broadcast a packet. This causes the sender nodes to broadcast the packet at the same time. We have seen in the earlier experiment that directional transmissions and receptions ensure the signal strength of packet sent from paired sender node are the highest. The results also show that the difference in RSSI between the packets is $> 3dB$, which is the co-channel interference tolerance level of the CC2420. In this experiment, we expect because of the capture effect to receive *only* the packet with the higher RSSI from the paired sender node even in presence of other concurrent packet transmissions from the unpaired sender nodes.

We collect around 30000 packets for both topologies. Fig. 7 (a),(b) show the results when nodes are arranged in a rectangular grid, and Fig. 7 (c),(d) show the results when nodes are arranged linearly. In the graph, the bar plots of some sender nodes are not visible because the PRR is zero or close to zero. The graph clearly shows that configuring both the sender and receiver to directional mode allows us to establish communication between paired nodes with high packet



(a) Node 1(R1) (b) Node 2(R2)

Fig. 6: Mean RSSI of received packets from different sender nodes with nodes arranged linearly. *Configuring the direction of the SPIDA Antenna helps to reduce intra-path interference.*

reception ratio (PRR). Fig. 7(b) and Fig. 7 (c),(d) show that configuring only the sender or the receiver to directional mode results in lower PRR. This is expected since the difference in RSSI between packets is close to 3 dB or less in the figures in the previous section. These experiments suggest that we can establish simultaneous communication flows on the same wireless channel using directional transmissions and receptions.

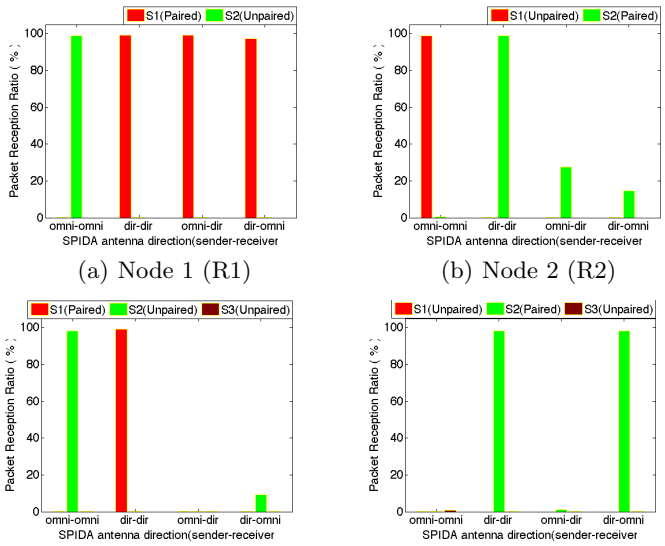
4 Discussion and Conclusion

Our experiments suggest that directional transmissions and receptions alleviate contention and can reduce intra-path interference in a linear network. Woo and Culler have shown that intra-path interference is a problem for reliable delivery of data in multi-hop wireless networks that is hard to avoid [10]. This is aggravated for high goodput bulk data transmission protocols such as Flush [5]. Therefore, protocols like PIP use channel diversity to avoid intra-path interference and improve end-to-end throughput [6]. Since there are only two IEEE 802.15.4 channels that do not overlap with the frequencies used by WiFi, channel diversity may require the use of channels that are interfered by WiFi.

The results of our experiments suggest that using directional transmissions and receptions we can avoid intra-path interference without using multiple channels. The latter also helps decrease protocol complexity and opens the possibility of high goodput multi-hop paths using a single wireless channel.

Acknowledgements

This work has been supported by the WISENET center at Uppsala University.



(a) Node 1 (R1) (b) Node 2 (R2)

(c) Node 1 (R1) (d) Node 2 (R2)

Fig. 7: Packet Reception Ratio(PRR) for receiver node 1 and 2. Nodes arranged in rectangular topology for (a) and (b). Nodes arranged in linear topology for (c) and (d). *A high PRR is observed from paired nodes when both sender and receiver are configured to directional mode.*

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