Modeling an Electronically Switchable Directional Antenna for Low-power Wireless Networks

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ABSTRACT

We present an empirical link-layer model of an electronically switchable directional antenna for low-power wireless networks. By virtue of directed transmissions, such antennas alleviate wireless contention and increase the communication range at no additional energy cost. In addition, the ability to dynamically change the direction of maximum gain allows to steer the radiated power in different directions on a per-packet basis. However, the few protocols that leverage such features are usually based on abstract antenna models, and are thus of limited applicability. On the contrary, we base our model on extensive real-world experiments using an existing antenna prototype we built. Our model mimics the temporal variations caused by environmental dynamics. We are currently embedding our model in the Cooja simulator, enabling the investigation of protocols leveraging this antenna technology in networks of arbitrary size.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—Wireless Communication

General Terms

Design, Experimentation, Measurement

1. INTRODUCTION

In contrast to traditional omni-directional antennas, directional antennas concentrate the radiated power only in given directions. This increases the communication range at no additional energy cost and alleviates the contention on the wireless medium. As a result, these antennas lower the network diameter and reduce packet collisions. In addition, electronically switchable directional antennas can *dynamically* change the direction of maximum gain on a per-packet basis. Very few existing protocols exploit this functionality. Most often, their design builds upon abstract antenna models [5], resulting in limited real-world applicability.

In contrast, we build a model of the link-layer performance of an electronically switchable directional antenna based on extensive real-world experiments. We leverage an antenna prototype called SPIDA [2, 3], shown in Figure 2. SPIDA is a *switched parasitic element* antenna designed for the 2.4 GHz band. The parasitic elements can be switched between ground and isolation, reflecting or directing the radiated power, respectively. SPIDA has six such elements, yielding six possible "switches" to control the direction of transmission. The antenna is integrated with the TMote Sky node and comes with Contiki drivers to control the parasitic elements.

Our model mimics the temporal variations caused by the environmental dynamics. The existing abstract models, largely based on analytical equations verified only in controlled laboratory experiments, do not account for such aspects. We are currently integrating the model in the Cooja simulator, enabling the accurate study of network protocols leveraging dynamically steerable directional communication in networks of arbitrary size.

We describe our methodology in Section 2 and our model in Section 3. Section 4 illustrates its ongoing integration in the Cooja simulator. Section 5 concludes.

2. METHODOLOGY

We apply a methodology akin to that of Cerpa et al. [1], who modeled the behavior of omni-directional antennas in the 400-900 MHz band. Besides the different band, we need to deal with two additional variables. Unlike standard antennas, the SPIDA behavior changes depending on the grounded/isolated parasitic elements. Moreover, the antenna behavior is not isotropic. Thus, we must characterize the sender-receiver physical relation with at least two variables describing coordinates in a plane, rather than simply with distance.

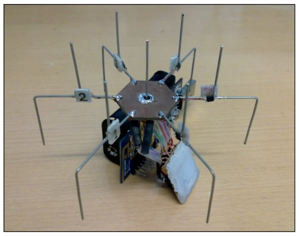
Figure 1: SPIDA prototype, connected to a TMote Sky.

We setup a test network with a SPIDA-equipped TMote Sky in front of a 4x4 grid of standard TMote Sky, as shown in Figure 2(a). SPIDA has only one parasitic element isolated, directed towards the center of the grid. The standard TMote Sky act as probes, uniformly sampling the environment where SPIDA radiates the highest power. We already verified that the packet delivery rate (PDR) is null in other directions [3]. We deploy the nodes in an open grass field, atop 1 m tall cardboard pillars to avoid signal reflections from the ground, as shown in Figure 2(b). Distances and transmission power are set to find a compromise between logistic issues and spatial accuracy. We also verify that the location has no interference from other networks in the ISM band. Before the experiments, we check that all probes do not exhibit significant drifts in the RSSI

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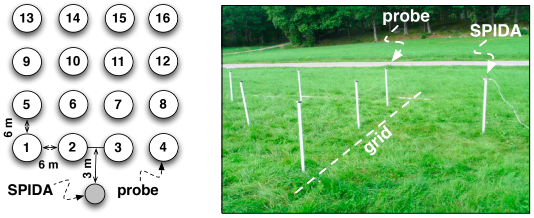
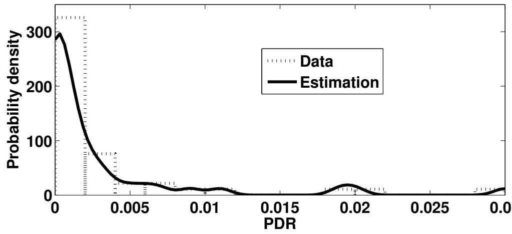
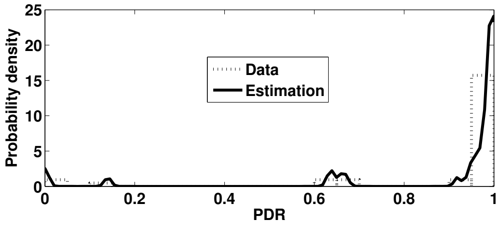


(a) Network layout (b) Experiment environment

Figure 2: Network layout and environment for experiments.



(a) Node 1: outside SPIDA main lobe.



(b) Node 7: inside SPIDA main lobe.

Figure 3: PDF at different probe nodes.

readings among each other when in comparable conditions.

In every experiment, the SPIDA node starts by broadcasting a `start` packet at the highest transmission power to synchronize the probes and inform them on the expected duration of the run. Then, it switches to a lower transmission power and transmits 1000 `test` packets with an inter-packet interval of 500 ms. This makes each packet independent of each other [4], avoiding the bias due to bursts of packet losses. The probes log the received packets, along with their $RSSI$ as indicated by the radio chip. At the end of the run, they report back to the SPIDA node the average PDR and $RSSI$. We repeat such experiment about 50 times in highly varying environmental conditions.

3. MODEL

We consider the average PDR and $RSSI$ obtained from every probe node as instances of a random variable. We then apply kernel density estimation to identify the corresponding probability density function (PDF). Such method is particularly accurate in the absence of information on the underlying probability distribution. The data we obtain grants a 95% confidence interval.

Figure 3 depicts two example PDFs for PDR obtained at different probes. Figure 3(a) corresponds to a probe outside the main transmission lobe. The PDF indeed shows a single maximum for low values of PDR, although some packets may still be occasionally received. We show in Figure 3(b) the PDF for PDR at a node in the middle of the transmission lobe: the situation is opposite to Figure 3(a), as the PDF shows a maximum for high values of PDR. We also obtain PDFs for nodes in a grey area at the boundary of the main transmission lobe, where the PDF exhibits multiple peaks. Similar considerations hold for $RSSI$.

By discretizing such curves, we generate probability tables with arbitrary granularity that associate given probability densities with specific values of PDR and $RSSI$. We use these tables to obtain the corresponding empirical cumulative distribution functions (ECDFs). Based on these, we can apply inverse transform sampling to generate new random values with the same statistical trends as the original data. This method requires the generation of uniformly distributed random numbers. It is thus amenable to implementation using pseudo-random number generators.

4. ONGOING WORK

We are currently integrating the model in the Cooja simulator, exploring different trade-offs between accuracy and simulation time. We choose to perform the PDF discretization off-line and directly feed Cooja with the ECDFs. Although doing it on-line would allow the user to choose an arbitrary granularity for the discretization step, we found that beyond a given threshold the accuracy of the ECDFs does not improve significantly.

Our model explicitly describes the antenna behavior at 16 points. To simulate transmissions at arbitrary points in space, two options are available: *i*) the *nearest neighbor* method, whereby we simply apply inverse transform sampling using as input the ECDF of the closest point in space, and *ii*) *interpolation*, whereby we select a given number of points in the vicinity of the considered point and then apply a form of interpolation to compute the required ECDFs.

The latter method, albeit more computationally intensive, is also more accurate. We can alleviate the processing overhead by caching the results of the interpolation step. If the nodes do not move, it will be necessary to perform the interpolation only the first time a packet is sent with a given antenna configuration. For the following packets, the simulator will simply look up the resulting ECDFs from the cache. We are currently implementing the model using this technique, which also allows us to easily experiment with different interpolation schemes.

5. CONCLUSION

We presented our ongoing work in modeling the link-layer performance of an electronically switchable directional antenna for low-power wireless networks. Our modeling techniques are based on extensive real-world experiments. The model we derive mimics the temporal variations due to environment dynamics. We are currently integrating the model in the Cooja simulator, enabling the study of network protocols leveraging such antenna technology in networks of arbitrary scale.

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