Rapid Prototyping over IEEE 802.11

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Abstract—This paper introduces Prawn, a tool for rapid prototyping communication protocols over IEEE 802.11 networks. Prawn provides a software environment that makes prototyping as quick, easy, and effortless as possible and thus allows researchers to conduct both functional assessment and performance evaluation as an integral part of the protocol design process. Since Prawn runs on real IEEE 802.11 nodes, prototypes can be evaluated and adjusted under realistic conditions. Once the prototype has been extensively tested and thoroughly validated, and its functional design tuned accordingly, it is then ready for implementation. Prawn facilitates prototype development by providing: (i) a set of building blocks that implement common functions needed by a wide range of wireless protocols (e.g., neighbor discovery, link quality assessment, message transmission and reception), and (ii) an API that allows protocol designers to access Prawn primitives. We show through a number of case studies how Prawn supports prototyping as part of protocol design and, as a result of enabling deployment and testing under real-world scenarios, how Prawn provides useful feedback on protocol operation and performance.

I. INTRODUCTION

Designing protocols for wireless networks poses countless technical challenges due to a variety of factors such as node mobility, node heterogeneity, power limitations, and the fact that the characteristics of the wireless channel are non-deterministic and can be highly variant in space and time. This implies that testing and evaluating such protocols under real operating conditions is crucial to ensure adequate functionality and performance.

In fact, the networking research community has already acknowledged the importance of testing and evaluating wireless protocol proposals under real-world conditions. As a result, over the last few years, a number of testbeds, such as Orbit [1], UnWiReD’s testbed [2], Netbed [3], and Roofnet [4], [5], as well as implementation tools, such as Click [6] and XORP [7], have been developed to support the deployment and evaluation of wireless protocols under realistic scenarios.

As illustrated in Figure 1a, there are mainly three evaluation methodologies commonly used when designing communication systems, namely mathematical analysis, simulation, and emulation. In this paper, we go a step further and advocate including rapid prototyping as an integral part of the design process (cf., Figure 1b). This will enable performing correctness verification, functionality and performance tests under real operating conditions early enough in the design cycle that resulting feedback and insight can be effectively incorporated into the design. Rapid prototyping is complimentary to current testbeds and tools which are typically used to produce a beta version of the final implementation, a step just before public release. Therefore, testing a protocol under real conditions often happens at the end of the development cycle or even after it is over.

We postulate that what is needed is a tool that makes prototyping as quick, easy, and effortless as possible. To this end, we introduce Prawn (PRototyping Architecture for Wireless Networks), a novel software environment for prototyping high-level (i.e., network layer and above) wireless network protocols. Prawn’s approach to rapid prototyping is based on two main components:

- The Prawn Engine, a set of basic building blocks atop which protocols and services can be prototyped. These building blocks include functions such as neighbor discovery, link assessment, and device configuration.
- The Prawn Library, an API that provides protocol designers with easy and transparent access to the underlying building blocks. Prawn deliberately provides a concise set of communication primitives, yet sufficient for a wide range of high-level wireless protocols.

Prototypes implemented with Prawn are not expected to be optimized, offering edge performance. Rather, our focus with Prawn is on obtaining, quickly and with little effort, a complete and fully functional instantiation of the system. Prawn makes prototyping as simple as writing network simulation scripts, with the difference that testing is done under realistic condi-
Assessing these conditions is done through the Prawn Engine, which runs as a background process that proactively performs tasks such as neighbor discovery and link quality assessment. This feature allows Prawn to provide accurate and up-to-date feedback from the wireless interface.

As shown by the several case studies presented in this paper, Prawn prototypes can be used for functional assessment as well as both absolute and comparative performance evaluation. Once the prototype has been extensively tested and thoroughly validated, and its functional design tuned accordingly, it is then ready for final implementation (which is out of the scope of Prawn).

In summary, Prawn’s contributions are as follows.

1) Prawn enables rapid prototyping which is key to testing and evaluating network protocols and services under real operating conditions as early as possible in the design cycle.

2) Prawn provides an easy-to-use and extensible prototyping interface which makes prototyping considerably simpler and faster requiring only basic programming skills. Prawn is to “live” experimentation what scripts are to simulations. Furthermore, new primitives can be easily incorporated as needed.

3) Prawn includes a flexible active neighborhood discovery mechanism which provides configurable neighborhood probing and power control mechanisms.

The remainder of this paper is organized as follows. We put our work on Prawn in perspective by reviewing related work in the next section. Section III provides an overview of Prawn, while in Sections IV and V we describe Prawn’s two main components in detail. We evaluate the overhead introduced by Prawn in Section VI and present in Section VII a number of case studies showing how Prawn makes prototyping fast and simple. Finally, we present our concluding remarks and directions for future work in Section VIII.

II. RELATED WORK

Simulations are perhaps the most widely used methodology for evaluating network protocols. They allow designers to evaluate the system at hand under a wide range of conditions (e.g., different mobility models, node heterogeneity, varying channel conditions). They also allow the exploration of the design space by enabling designers to vary individual protocol parameters (e.g., timers) and combinations thereof. Finally, they are instrumental for scalability analysis and they offer reproducibility. Examples of well known simulation platforms include NS-2 [8], OPNET [9], GloMoSim [10], and QualNet [11].

Emulation tries to subject the system under consideration to real inputs and/or outputs. Environments like EMPOWER [12] or Seawind [13] emulate the wireless medium by introducing packet error rates and delays. Other emulators like m-ORBIT [14] also emulate node mobility by space switching over a testbed of fixed nodes. A key advantage of emulation in the context of wireless/mobile networks is to facilitate testing by avoiding, for example, geographic and mobility constraints required for deployment.

More recently, a number of projects have pioneered the field of wireless protocol evaluation under real conditions. They include testbeds such as Orbit [1], Emulab [19], Roofnet [5], Mint-m [4], the work reported in UnWiReD [2] and Netbed [3], as well as tools that support protocol implementation like the Click modular router [6] and XORP [7]. As previously pointed out, such tools and Prawn have different goals, address different phases of the design process, and are therefore complementary. While tools like Click and XORP target the final implementation at the final stages of protocol design, Prawn focuses on prototyping a research proposal at the very early stages of the design process. Therefore, through Prawn, protocol designers can very quickly and easily generate a fully functional, but non-optimized, implementation for live testing in real scenarios.

In the context of wireless sensor networks (WSNs), Polastre et al. [20] propose SP (Sensornet Protocol), a unifying link abstraction layer. SP runs on TinyOS [21] and provides an interface to a wide range of data-link and physical layer technologies. Prawn and SP roughly share the same functional principles, e.g., data transmission, data reception, neighbor management with link quality, etc. However, they have quite different goals. First, SP only manages the neighbor table; it neither performs neighbor discovery nor provides link assessment. Second, SP is designed for WSNs whereas Prawn is for general IEEE 802.11 networks. Finally, while SP aims at optimizing the communication and unifying different link layers in WSNs, Prawn aims at facilitating and simplifying prototype implementation.

EmStar [22] is another development environment for WSNs and runs on the Intel Stargate platform [23]. It is similar in essence to Prawn since it provides a set of primitives that upper layers can use. However, EmStar supports implementation by focusing on modularity and code reuse. Its architecture is quite complex and its use requires quite sophisticated development skills when compared to Prawn standards.

MAPI [24] is an API especially developed for wireless networks based on the Wireless Tools [25]. It provides a set of simple primitives to obtain information from the underlying wireless device. Besides accessing information from the wireless device through a simple API, Prawn also runs an active daemon that performs neighborhood discovery with link quality assessment, as well as sending/receiving mechanism.

III. PRAWN OVERVIEW

Prawn targets prototyping protocols and services at the network layer and above. Simplicity was a major goal we had in mind when designing Prawn; we wanted to ensure that learning how to use Prawn would be as intuitive and immediate as possible requiring only basic programming expertise. For example, in Prawn, sending a packet at a given transmit power

1Currently, Prawn targets IEEE 802.11 networks, although its design can be extended to run atop other wireless network technologies.

2Given the focus of this paper, we highlight related efforts that target wireless networks. However, similar tools for Internet research have been proposed; notable examples include VINI [15], PlanetLab [16], X-Bone [17], and Violin [18].
level is performed by a single primitive and takes one line of code. Our focus was thus to provide: (1) a concise, yet complete set of functions to realize high-level protocols and (2) a simple, easy-to-use interface to provide access to Prawn’s functionalities.

A. Prawn Architecture

Prawn consists of two main components: (i) the Prawn Library (cf., Section IV), which provides high-level primitives to send and receive messages, retrieve information from the network, etc; and (ii) the Prawn Engine (cf., Section V), which implements the primitives provided by the Prawn Library.

The current implementation of Prawn runs on Linux atop IP for backward compatibility with the global Internet. The interaction between the Prawn Engine and the physical wireless device relies on the Wireless Tools [25]. This set of tools allows retrieving information from most wireless devices as well as setting low-level parameters. Furthermore, it is available with most Linux distributions.

Prawn’s components, how they interact with one another and with the underlying operating system are illustrated in Figure 2. As highlighted in the figure, Prawn’s functionalities are accessible through the Prawn Library. Messages and requests received from the library are then processed by the Prawn Engine. The Prawn Library and Engine communicate with each other through the loop-back interface using a simple request/reply mechanism. This choice simplifies modularity and portability.

B. How to Use Prawn

Running Prawn requires only a few basic steps. First, it needs to be configured and installed on the machines that will be used in the experiments. In particular, in the Prawn configuration file it is necessary to set the names of the wireless interface and network (e.g., the ESSID). Optionally an IP address can be specified. Otherwise, Prawn will randomly generate an IP address in a default subnetwork.

Using Prawn itself only requires two operations (as described below), namely executing the Prawn Engine and including the Prawn Library in the prototype code.

1: Starting the Prawn Engine. Prawn is distributed under GPL license and available online [26]. Once compiled, the Prawn Engine is launched as a command line program on machines connected in “ad hoc” mode. Prawn is supposed to run in daemon mode, but can run in console mode for debugging purposes. As stated before, Prawn provides a number of options that can be set/configured at the execution of the Engine. They are listed in Table I. Other options (e.g., the number of lost beacons required to consider that a node is no more a neighbor) are tunable in the prawn.cfg configuration file.

2: Using the Prawn Library. The Prawn Library (described in detail in Section IV) is composed of a set of primitives that are linked to the prototype through standard include files. Currently, prototypes can be developed either in C or in Perl (a Java version is about to be released). For C development, the file prawn.h should be included in the header of the prototype code. Similarly, the file prawn.pl is to be included for prototypes developed in Perl.

C. “Hello World!”

To illustrate the use of Prawn, we describe how to implement a simple “hello world” prototype using Prawn’s Perl library. In this example we send a message from Bob to Alice.

**Step 1.** Launch Prawn with “prawn -d -N Bob” in the first machine and “prawn -d -N Alice” in the second machine.

**Step 2.** Get the first machine ready to receive messages by executing the following Perl script:

```perl
require "prawn.pl";
while(!@Message){
  @Message=Prawn::Receive()
}
print 'Received : ', @Message[4], ' from ', @Message[2], "
";
```

**Step 3.** On the other machine launch the following Perl script:
The result is trivial: Alice sends a “Hello World” message to Bob, and Bob prints “Received: Hello World from Alice” on the screen. However, this simple example aims at showing the level of abstraction provided by Prawn, where low-level system knowledge (e.g., sockets, addressing) is required. More elaborated examples will be presented in Section VII.

IV. THE PRAWN LIBRARY

The Prawn Library, currently implemented in C and Perl, provides a set of high-level communication-oriented functions. They hide from protocol designers lower-level features such as addressing, communication set-up, etc. Their syntax is quite simple and intuitive. Prawn’s current set of primitives addresses basic functions required when prototyping a high-level communication protocol; nevertheless, Prawn was designed to be easily extensible allowing new primitives to be implemented and integrated. The primitives currently available are:

- **Prawn_Info()**: Returns information on the configuration of the local Prawn Engine. Basically, it consists of the list of settings chosen when launching the daemon (cf., Table I). Some examples are the node’s ID, interface port number, and beacon period.
- **Prawn_Neighbors()**: Returns the list of the node’s one-hop and two-hop neighbors as well as statistics concerning the quality of the respective links. In Section V, a thorough explanation of the information returned by the Engine will be given.
- **Prawn_Send(Message, ID, TX_Pwr)**: Sends Message to node ID; the optional argument TX_Pwr can be used to explicitly set the transmit power to be used during the transmission. Message can be a string, a number, a data structure, or any other data or control message, depending on the prototyped protocol (e.g., a route request primitive of a route discovery protocol).
- **Prawn_Send_Broadcast(Message, TX_Pwr)**: Sends a broadcast message containing Message; in a similar way to Prawn_Send(), the optional argument TX_Pwr allows to set the transmit power.
- **Prawn_Receive()**: Checks if a message has been received; if so, the message is returned. This primitive is non-blocking: if no message has been received, it just returns zero.

V. THE PRAWN ENGINE

The Prawn Engine is event-driven, i.e., its main process remains asleep waiting for an event to occur. An event can be triggered by a request from the Prawn Library (coming through the loop-back interface) or by a message received on the wireless interface. The main loop of the Engine is described in pseudo-code in Algorithm 1. The main events are:

Control Event: Prawn performs some tasks on a regular basis controlled by a timer. For instance, a timeout event triggers the transmission of neighborhood discovery control messages (beacons or beacon replies, cf. Sections V-B and V-C).

Client Request: This is an asynchronous event. It is triggered by a library call, requesting an action from the engine (e.g., sending a packet or retrieving the current neighbor list).

Neighbor Message: This event is also asynchronous. It is triggered when messages from neighbors are received through the wireless interface. These can be either control messages to be processed by the engine or user messages to be delivered to the prototype through the library’s primitive Prawn_Receive().

A. Packet Format

All packets transmitted by Prawn start with a one-byte Type field that defines the structure of the rest of the packet. In its current version, Prawn defines four types of packets as shown in Table II.

B. Beaconing

To build and maintain the list of neighbors, each node running Prawn broadcasts 24-byte beacons periodically. The beacon period is configurable depending on the requirements of the prototype under development. By default, the Prawn Engine is configured to test connectivity under different power levels (useful for instance to prototype topology control algorithms based on power control [27], [28]). The Prawn Engine applies a round-robin policy to continuously change the transmit power. A beacon is first broadcast with the lowest power value. The transmit power level is successively increased for each beacon, up to the maximum transmit power. We call this sequence of beacons a cycle. The different values of the transmit power are either obtained from the interface

### Algorithm 1: The Prawn Engine’s main loop.

```plaintext
1: Timeout := time_to_next_regular_event
2: while 1 do
3:   if (Timeout) then
4:     Perform regular operation
5:     Timeout := time_to_next_regular_event
6:   else if (Client Request) then
7:     Perform requested action
8:   else if (Neighbor Message) then
9:     if (Message == Data) then
10:    Send packet to the client process
11:   else if (Message == Control) then
12:    Update neighborhood list and statistics
13:   end if
14: end if
15: end while
```

| Type | Function    |
|------|-------------|
| 0    | Reserved    |
| 1    | Beacon      |
| 2    | Data        |
| 3    | Feedback    |
or set by the user. This cycle is then repeated at every beacon period. This way, the time elapsed between two beacons sent with the same transmit power is equal to the beacon period.

Of course, the power control feature is optional, depending on the designer’s needs. If this feature is disabled, each cycle is then composed of only one beacon, sent at the default transmit power level. The number of transmission power levels and their values are customizable, depending on the power control features provided by the wireless interface under utilization.

The beaconing packet format, which is illustrated in Figure 3, includes the following fields:

- **Type**: This field is set to ‘1’ (cf., Table II).
- **Transmit Power**: Transmit power used to send the beacon.
- **Transmitter ID**: Sender identifier.
- **Beacon Period**: Time period between two beacons transmitted with the same power level (set by the user).
- **MAC Address**: MAC address of the transmitter.
- **Sequence Number**: Sequence number of the beacon.

Upon the reception of a beacon (or sequence of beacons if different transmit powers are used), various statistics can be derived. For instance, a node A can determine, at a given point in time, the minimum transmit power that B should use to send messages to A. This value corresponds to the lowest transmit power among all the beacons received by A from B. Of course, the minimum transmit power may change over time, and will be updated along the successive cycles.

Configuring Prawn is important to achieve an adequate balance between performance and overhead. For example, sending beacons too frequently would generate high overhead. On the other hand, limiting the number of beacons is likely to result in out-of-date measures. For these reasons, the beaconing period is one of Prawn’s customizable parameters and its value is carried in the header of each beacon sent. A beacon is considered lost when the beaconing period (included in previous received beacons) times out. By default, a neighbor is removed from a node’s neighbor table when three consecutive beacons from this neighbor have been lost (or when three consecutive beacons for every transmit power have been lost).

The rationale for reporting the transmit power of the weakest beacon received from a particular neighbor is that it allows to roughly characterize the quality of the corresponding link. This estimation is also confirmed using the maximum received signal strength measured within a cycle.

Although destined to a single neighbor, feedback packets are broadcast and thus overheard by all one-hop neighbors. This way, nodes can obtain information on two-hop neighborhood (cf., Figure 5).

### C. Replying to Beacons

Nodes reply to beacons using 16-byte feedback packets, as shown in Figure 4. Feedback packets summarize neighborhood– and link quality information as perceived by the receiver of the beacons. This feature allows verifying the bidirectionality of links. Feedback packets are sent to every neighbor after a complete cycle. Prawn keeps sending feedback packets also in the case where a neighbor is considered lost (a unidirectional link may still exist between the two nodes). Feedback packets contain the following fields:

- **Type**: This field is set to ‘3’ (cf., Table II).
- **Destination ID**: Identifier of the neighbor concerned by the feedback.
- **Minimum Received Transmit Power**: Is the transmit power of the beacon received with the weakest signal strength from that particular neighbor.
- **Maximum Received Power Strength** (in dBm): Is the maximum signal strength measured when receiving beacons from that particular neighbor.

When a node calls the `Prawn_Neighbors()` primitive, the engine returns a data structure with information about the node’s neighborhood. This information can be also obtained by running Prawn in console mode, e.g., for debugging purposes. Figure 5 shows a snapshot of the information returned by the Prawn Engine running in console mode on a node named “Bob”. This snapshot shows a list of Bob’s neighbors, along with statistics on last beacons received by each neighbor for every transmit power. Basically, Bob has two active neighbors, John and Alice. The link between Bob and Alice has, on average, better quality than the one between Bob and John; indeed for beacons sent at 1 mW and 12 mW, only 4/5 of them have been received.

Note that if the power control feature is disabled, then the cycle is unitary.
As previously described, neighborhood information is obtained through beacons and feedback packets. More specifically, broadcast beacons are used to build the list of direct neighbors. This list is established by gathering the transmitter ID of each received beacon. Moreover, data included in beacons and feedback packets inform each node what is the minimum transmit power required to reach a neighbor. Such information is of primary importance in assessing link quality. Another prominent link characteristic is the error rate, which is determined according to the beacon period included in each beacon transmitted. The Engine considers a beacon as lost when it is not received within the beacon period indicated by the corresponding neighbor. The size of the receiving window used to compute the error rate is customizable. For instance, in Figure 5, the error rate for John’s packets transmitted at 12 mW is 1/5, because over the 5 most recent 12 mW beacons transmitted by John, only 4 have been received.

When receiving a beacon, the Prawn Engine retrieves and saves the received signal strength. Along with the transmit power of the beacon (which is also included in the beacon), the received signal strength returned by the engine helps to evaluate the signal attenuation. The difference between the transmitted power level indicated in the beacon and the signal strength measured when the beacon is received can also be used by a protocol to characterize link quality.

E. Sending and Receiving Messages

Two other key functions performed by the Prawn Engine are transmission and reception of data (triggered by the Prawn_Send() and Prawn_Receive() primitives, respectively). The engine is in charge of the communication set up, namely opening sockets, converting the receiver identifier to a valid IP address, encapsulating/decapsulating packets, and adjusting the transmit power before transmission. Figure 6 shows the structure of the data packets, which contain the following fields.

- Type: This field is set to ‘2’ (cf., Table II).
- Transmit Power: Power used to send the packet.
- Payload Size: Size of the payload field.
- Payload: Data being sent.

VI. PERFORMANCE OF PRAWN

In this section, we present our measurements of the overhead introduced by Prawn (in terms of delay and throughput) on the different platforms that compose our testbed. We show that Prawn delivers adequate performance even in the case of platforms with limited computation– and memory capability.

A. Setup

The experiments reported here were performed using different platforms from our testbed, namely:

- 100-byte packets
- 1,400-byte packets

Data packets are sent using UDP to the corresponding IP address. This explains why their header does not need to include the destination ID.\footnote{Note that the same method cannot be used for beacons, since beacons are always sent broadcast at IP level and thus contain the broadcast address.} On the receiver side, the engine listens on an open socket for any incoming packets. Packets are then decapsulated and sent to the prototype which retrieves them by using the Prawn_Receive() primitive.
• **Laptop 1.** Dell Latitude X1 featuring and Intel Pentium M 733 Processor at 1.1 GHz, 1.2 GB of memory and an embedded Intel PRO/Wireless 2200BG 802.11b/g chipset. The Operating System (OS) is Linux Fedora Core 6, 2.6.18.2 kernel, with the ipw2200 driver.

• **Laptop 2.** HP Compaq nx7000 featuring an Intel Pentium M Processor at 1.4 GHz, 512 MB of memory and a Netgear WGS11T 802.11b/g wireless Cardbus adapter. The operating system is Linux Fedora Core 6, 2.6.18.2 kernel, with the madwifi-ng driver for Atheros chipsets.

• **Mini-Pc.** VIA Eden EBGA fanless processor at 600 MHz, with 512 MB of memory and a Cisco Aironet 802.11a/b/g wireless PCI adapter (PI21AG-E-K9). The OS is Linux Fedora Core 5, 2.6.16.16 kernel, with the madwifi-ng driver for Atheros chipsets.

• **PDA.** Nokia N770 Internet Tablet, powered by a 250 MHz ARM based Texas Instruments 1710 OMAP processor, 64 MB of memory and an embedded 802.11b/g chipset. The OS used is the Nokia Internet Tablet OS2006 Edition.

Our experiments were performed in a research laboratory (i.e., indoors, under radio interference of existing wireless networks, etc.). Measurements were obtained between two nodes forming a one-hop topology.

### B. Average Delay

When sending a message, a prototype using Prawn calls the `Prawn_Send()` primitive. This function forwards the packet to the engine, which triggers an event. If not idle, the engine terminates its current tasks (e.g., sending/receiving a beacon, the engine, which triggers an event. If not idle, the engine terminates its current tasks (e.g., sending/receiving a beacon, receiving a packet) and encapsulates the message. Then it changes the transmit power (if requested) and sends the packet to the corresponding neighbor through the wireless interface. Our goal here is to measure the additional delay incurred by Prawn (without Prawn, a message would be sent directly to the wireless interface) and show that it is small enough compared to the overall message delivery delay.

To measure the additional delay incurred by Prawn, we implemented a simple application program that calls the `Prawn_Send()` primitive and records a timestamp. Then the Prawn Engine receives the packet from the loop-back interface, encapsulates it, changes the transmit power if requested, and generates a second timestamp just before the packet is finally sent through the wireless interface. Experiments have been performed for two different packet sizes, namely 100– and 1,400 bytes.

Tables III and IV show the results when running Prawn on our testbed laptops. Reported averages were obtained over 10,000 measures. These results are quite encouraging as additional delays of up to 0.20 ms for sending a message are quite reasonable for the purposes of a prototype.

Measured delays for the the mini-PC and the Nokia N770 which exhibit already high throughput, are quite reasonable for the purposes of a prototype. Nevertheless, we argue that when testing protocol functionality and correctness, achieving high throughput is not critical. Indeed, most target protocols such as routing, topology control, localization, addressing/naming schemes, etc. generate typically short control messages relatively sparse in time.

### D. Communication Overhead

The communication overhead incurred by Prawn is due to its beacons, feedback messages, as well as additional message headers. This overhead can be easily estimated as shown in the following example. Let us consider a Prawn prototype running on a 6-node wireless network where nodes are all in range of one another. The beacon period is set to the default value of 5,000 ms, and 5 different transmit power levels are used.

Recall that IEEE 802.11a/g (we used 802.11g in our experiments) has a maximum nominal transmission rate of 54 Mbps. Actually, this is the rate for the payload of 802.11 frames; headers, trailers, and handshake packets are sent at lower rates, which makes the effective throughput drop below 40 Mbps.

### C. Throughput

We also measured the maximum throughput supported by Prawn. To this end, we compared the throughput of two Perl scripts communicating by sending data directly through the wireless interface (i.e., without Prawn), against having them send data using Prawn’s send/receive primitives. Results for the laptop nodes are presented in Tables VII and VIII.

These results are again very encouraging: the throughput achieved with Prawn is comparable to what was obtained without Prawn, which shows that the overhead introduced by Prawn is mostly negligible. However, as shown in Tables IX and X, this is not the case for the less capable platforms, namely the mini-PC and Nokia N770 which exhibit already very low throughput without Prawn. The per-packet processing performed by Prawn increases the bottleneck, limiting throughput further.

### Appendix A

| Table VII: Average throughput using Prawn on a Dell Latitude X1 laptop. |
|---------------------------------------------------------------|
| **100-byte packets** | **1,400-byte packets** |
| **Without Prawn** | **With Prawn** |
| 3.0 Mbit/s | 3.1 Mbit/s | 17.9 Mbits/s | 18 Mbit/s |

| Table VIII: Average throughput using Prawn on a HP Compaq nx7000 laptop. |
|---------------------------------------------------------------|
| **100-byte packets** | **1,400-byte packets** |
| **Without Prawn** | **With Prawn** |
| 4.7 Mbit/s | 4.9 Mbit/s | 25.6 Mbits/s | 25.9 Mbit/s |

| Table IX: Average throughput of mini-PC. |
|---------------------------------------------------------------|
| **100-byte packets** | **1,400-byte packets** |
| **Without Prawn** | **With Prawn** |
| 2.2 Mbit/s | 5.4 Mbit/s | 11.6 Mbits/s | 22.2 Mbit/s |

| Table X: Average throughput of Nokia N770. |
|---------------------------------------------------------------|
| **100-byte packets** | **1,400-byte packets** |
| **Without Prawn** | **With Prawn** |
| 0.3 Mbit/s | 0.8 Mbit/s | 2.3 Mbits/s | 4.9 Mbit/s |
for the beacons. Thus, during a beacon period each node: (1) broadcasts 5 beacons (one for each transmit power) and (2) broadcasts 5 beacon replies (one for each neighbor). We also have to account for an additional 4 (header) bytes per packet.

For the case that the prototyped protocol sends 5 beacons (one for each transmit power) and (2) broadcasts 5 beacon replies, and (3) sends 200 bytes for data packet headers. The corresponding overhead is 120 bytes for the beacons, 80 bytes for the beacon replies, and 200 bytes for data packet headers. We obtain 400 bytes of overhead per beacon period, or 640 bits/s. Since we have 6 nodes in the network, the overhead for the whole network is 3.84 Kbit/s.

The important point here is that, as long as protocol designers understand the cost incurred by Prawn, they can, besides testing their prototype under real conditions, also conduct absolute/relative overhead analysis.

VII. PROTOTYPING WITH PROW

Prawn is intended to be a tool for prototyping a wide range of communication algorithms for heterogeneous wireless networks. In this section, we first illustrate the use of Prawn through a number of case studies, highlighting its range of applicability and ease of use as well as how it can be employed to evaluate and test protocols.

A. Case Study 1: Neighborhood Monitoring

In this case study we use Prawn to implement a simple neighborhood monitoring protocol. The purpose of this example is to show how Prawn simplifies neighbor discovery and link quality assessment. The experimentation setup was as follows: four heterogeneous nodes running Prawn were placed at different locations in our lab as depicted in Figure 7. This figure also lists the types of nodes (for further details, see Section VI).

We used a fifth node running Prawn executing a simple script registering the received signal strength data collected by the moving node. It is interesting to remark how at the beginning of the experiment the laptop has only two direct neighbors: the PDA and the MiniPC-1. Indeed the curves for the other two nodes appear only after 20 seconds. The same information can be deduced from Figure 9, which depicts a snapshot of the feedback received by Prawn in console mode. The same figure shows that the other two nodes (MiniPC-2 and Laptop-2) are in the two-hop neighborhood of the moving laptop. It can be also observed that at the end of the experiment the laptop has only three direct neighbors; indeed the PDA becomes too far and its curve in Figure 8a ends after around 75 seconds. This is also confirmed in Figure 10, which lists all the fixed nodes but has the PDA marked as dead.

We compared the received signal strength results obtained with the Prawn prototype against what is reported by simulations of the same setup using NS-2 [8]. The discrepancy between the two sets of results clearly illustrates the importance of testing wireless protocols under real conditions. Prawn’s

6The reader is referred back to Section V for more details on how Prawn assumes that a node is no longer available.
value-added is that it makes prototyping protocols as simple and fast as implementing them on a network simulator.

B. Case Study 2: Node Localization in Wireless Mesh Networks

The previous case study can be extended for Wireless Mesh Networks (WMNs). In WMNs, mobile users connect to fixed wireless nodes (Wireless Mesh Routers – WMRs) belonging to the infrastructure. As illustrated in Figure 11, consider the case where WMR1, WMR2, and mobile node M are all neighbors (i.e., they are in range of one another). Then node WMR1 can approximately determine the direction of movement of M by measuring the received signal strength or the minimum transmit power of beacons received. In this particular example, suppose that WMR1 is experimenting decreasing link quality with M. WMR1 can use the feedback packets broadcast by another fixed node, say WMR2, to M. By examining these packets, WMR1 realizes that the link quality of WMR2 − M is not getting worse. Thus, WMR1 concludes M is moving approximately in the direction of WMR2. With this information, a routing process can choose to start forwarding packets to WMR2 in order to reach M. Note that this would also be very useful in the context of episodically-connected networks. Figure 12 shows a simple script that uses information from the Prawn Engine to find all neighbors of M sorting them by RSSI.

Furthermore, by using the maximum received signal strength (already included in the feedback packets), a node can estimate its neighborhood’s “virtual topology”, where distances between nodes are based on signal strength (i.e., are given in mW or dBm). Note that these “virtual distances” between nodes are not always proportional to euclidian distances, e.g., if the nodes are not in line-of-sight. Nevertheless, signal strength provides indeed a better characterization of link quality than the physical distance between nodes. By using simple trilateration (with 3 or more neighbors), nodes can compute their locations more accurately. For the example illustrated in Figure 11, node WMR1 can compute the location of M by trilateration, using its own RSSI (Received Signal Strength Indication) on the link M − WMR1, along with the RSSIs on the links M − WMR4 and M − WMR2 (broadcast respectively by neighbor nodes WMR4 and WMR2).

This particular example illustrates the use of Prawn’s features related to power control and signal measurements. It also show cases the modularity properties of Prawn’s prototypes, which enables code reused. In other words, Prawn code to implement basic functions like neighborhood discovery can be reused by other (more complex) prototypes.

C. Case Study 3: Prototyping Other Protocols

1) Flooding: Flooding is the simplest possible routing algorithm. Its basic operation is as follows: upon receiving
a packet, each node sends it once to all its neighbors. Thus the only requirement to implement this algorithm is to be able to receive and broadcast packets.

Prawn makes this algorithm easier to implement even for inexperienced programmers as they are abstracted away from lower-level functions like sockets, ports, addressing, etc. Flooding can be implemented simply by using the Prawn_Receive() and Prawn_Send_Broadcast() functions.

Figure 13 shows how short and simple the flooding prototype using the Prawn Library is. This 12-line piece of code has been running successfully on our testbed and we have conducted intensive experimentation that has enabled us to understand the behavior of the flooding algorithm under realistic conditions and with real users. This behavior is not obvious and known a priori from simulations; for example, Cavin et al. tried to simulate the flooding [29] algorithm using three different simulators namely, NS-2, OPNET, and GloMoSim, with exactly the same parameters and scenarios. Surprisingly, the results were considerably different, depending on the simulator used.

2) Network Coding: While the previous section illustrates the use of Prawn to prototype one of the simplest protocols, we show, in this section, that Prawn can also be used to prototype more complex protocols. In particular, we show case the use of Prawn to prototype network coding algorithms [30], [31]. For example, COPE, whose principles and implementation are described in [31], is clearly rather complex. Our goal here is to show that some evaluation of network coding proposals could be easily done without requiring a fully-functional implementation of the algorithm.

For clarity, we briefly explain the essence of network coding through a very simple example. In traditional forwarding, when a node A and a node B want to exchange data via a third node C, both send their packets to C, and then C forwards the packets to A and to B. Exchanging a pair of packets requires 4 transmissions. Using network coding, instead of sending separate packets to A and B, node C combines (e.g., using the XOR function) both packets received from A and B, and broadcasts the encoded packet. Since A knows the packet it has sent, it can decode the packet sent by B (e.g. applying again the XOR function) from the encoded packet received from C. Similarly, B can decode the packet sent by A from the same packet received from C. Thus, with this method, only 3 transmissions, instead of 4, are required.

Using Prawn, we implemented a prototype of the algorithm described above. As shown in the Perl code running on node C (Figure 14), the first received packet is stored in a standby variable ($Stdby), then the next packet is stored as @Msg. If the two stored packets are not received from the same node, then they are XORed and broadcast. If, instead, both packets are from the same node, it does not make sense to XOR them. In this case, the packet stored in standby is sent as a normal unicast packet, and the latest packet goes to the standby queue.

We also implemented a prototype of a traditional forwarding algorithm. We compare both implementations to measure the performance gains achieved by network coding when A sends 10,000 packets of 1,400 bytes to B and vice-versa. Without network coding, the total amount of data transmitted was 54 MB on both links. With network coding, only 44 MB were sent. With this code as a starting point, network coding protocol designers can test and tune their algorithms on real platforms under real conditions.

3) Topology Control: Topology control algorithms require updated information about neighbors. Selecting good neighbors is often beneficial for the whole network. Prawn supports various neighbors selection criteria relying on cross-layer information. For instance, in order to save energy and reduce interference, neighbors with lowest required transmit power can be selected. Conversely, neighbors with the highest signal strength received could be chosen. Many recent research efforts relying on cross-layer approaches would benefit from Prawn’s lower layer information.

The code in Figure 15 shows how to get in 7 lines a list of neighbors sorted according to their receive signal strength. This code is running successfully on our testbed consisting of heterogeneous nodes. An important point here is that the received signal strength value retrieved from the wireless driver can be different depending on the wireless device model.

7Of course, more elaborated variations of flooding exist, but here we consider it in its simplest form.

Fig. 13: Perl code of a flooding prototype

```perl
require "prawn.pl";
while(1){
  while(@Message)
    $Message = Prawn_RECEIVE(); } $msgID = unpack("n",$Message[4]);
  if (grep/$msgID/@ID_list){
    push(@ID_list,$msgID); Prawn_Send_Broadcast($Message[4]);
  }
  @Message = ();
}

Fig. 14: Perl code of a network coding algorithm

```
If the neighbors do not have all the same wireless cards, the selection could be biased. This is an example of practical issue that cannot be taken into account from simulations. Using Prawn, designers can evaluate their proposal taking into account the features and performance of off-the-shelf hardware and drivers.

VIII. CONCLUSION

In this paper we proposed Prawn, a novel prototyping tool for high-level network protocols and applications. Prawn’s main goal is to facilitate the prototyping of wireless protocols so that prototyping becomes an integral part of the design process of wireless systems.

Prawn is not an alternative to simulation or any other evaluation method. Instead, it stands as a complementary approach that goes beyond simulation by taking into account real-world properties. Prawn surfs the wave of recent research efforts toward making implementation easier (e.g., Click and XORP), but as a preliminary phase in this process. The designer has to keep in mind, however, that the performance of a prototype does not always match exactly with the performance of a final and optimized implementation. Nevertheless, it is not the same gap we can observe between simulation results and real implementation results. In simulation it is very difficult to estimate how far a model is from reality and the exact impact it has on the performance results. Using Prawn, an estimation (even rough) can be deduced from the observed overhead.

Unlike existing implementation tools, Prawn provides a general, simple, concise, yet sufficient set of functions for a wide range of high-level algorithms, as well as an API that shields the designer from low-level implementation details. Through several case studies, we showcased the use of Prawn in the context of a wide range of network protocols. But the possibilities of Prawn are not restricted to the examples given in this paper. Other experiments where Prawn can be useful include: evaluating existing protocols for wired networks in the wireless context, implementing new routing protocols, testing overlay approaches in wireless multi-hop networks, evaluating distributed security algorithms, testing new naming mechanisms over IP, testing incentive mechanisms for communities, implementing localization algorithms, measuring wireless connectivity in both indoor and outdoor scenarios, evaluating peer-to-peer algorithms, testing opportunistic forwarding mechanisms.

We hope our work will provide a starting point for an improved design methodology as prototyping provides both easy and accurate evaluation of wireless protocols and services under real conditions. This paper has demonstrated that this is feasible – Prawn is a fully-functional tool that responds to the needs of early protocol evaluation. Finally, we expect that Prawn’s simplicity will allow researchers to adopt it. To help this becoming true, ongoing work includes adding new prototyping facilities, releasing a Java version of the Prawn Library, and porting Prawn to other operating systems such as FreeBSD and Windows.

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