Framework for characterizing hardware deployed in Wireless Mesh Networking Testbeds

Marc Portoles-Comeras, Manuel Requena-Esteso, Josep Mangues-Bafalluy

| Publication: | Proc of the 3rd Tridentcom |
| Vol: | |
| No.: | |
| Date: | May 2007 |

This publication has been included here just to facilitate downloads to those people asking for personal use copies. This material may be published at copyrighted journals or conference proceedings, so personal use of the download is required. In particular, publications from IEEE have to be downloaded according to the following IEEE note:

© 2007 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.
Framework for characterizing hardware deployed in Wireless Mesh Networking Testbeds

Marc Portoles-Comeras, Manuel Requena-Esteso, Josep Mangues-Bafalluy
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)
Parc Mediterrani de la Tecnologia (PMT)
Av. Canal Olímpic S/N 08860 Castelldefels - Barcelona - Spain
{marc.portoles,manuel.requena,josep.mangues}@cttc.es

Abstract—Experimental systems introduce a variable in the analyzed system which is not present in theoretical ones, i.e. real equipment from different vendors. Given a certain standard, different vendors might take different design choices depending on the target equipment being devised. As a consequence, though this equipment fulfills the same functionality, it shows different behavior in equivalent scenarios due to parameters such as power constraints, degree of standard compliance, or CPU processing power. In this paper, we identify and explain the implications that these parameters have on the performance of wireless equipment, with particular emphasis on building a wireless mesh networking testbed. Moreover, this paper outlines techniques and recommended practices to use when selecting equipment in order to assess its behavior. It presents also practical quantitative results illustrating the type of results obtained and the validity of the techniques and procedures proposed.

Keywords—Wireless mesh network deployment, assessment methodology, hardware decision, experimental approach.

I. INTRODUCTION

Wireless networking research has become highly experimental. The availability of off-the-shelf hardware tools and the increasing capabilities and functionalities of commodity computers has pushed this move. Several testbeds and experimentation facilities (see [1], [2], or [3]) are being developed to provide realistic environments to design and test protocols and algorithms for wireless networking. Additionally, a number of public data repositories (see [4] for a reference) have been recently made available to researchers to push up the development of realistic modeling.

When reviewing recent literature on the development of wireless research testbeds there are a number of observations to be raised. First, one can notice that there have been used, practically as many hardware solutions as testbeds can be found in the literature. Wireless nodes come in several different form factors, with different network device models and even carrying a variety of antenna solutions. Typically, one relies on the fact that products from different vendors following the same standard specification behave comparably, but this has been shown not to hold always true (see [5] or [6]). Second, there exist few references in the literature on how devices are (or should be) tuned up. There is a high risk that experimenters just plug wireless devices in commodity computers and start raising non-accurate conclusions out of the observations.

Calibrating the equipment to be used helps experimenters in validating the results obtained out of experimentation. Correct (incorrect) theory can be too promptly discarded (accepted) in the view of non-precise experimentation results. Finally, literature studying design options for the development of wireless testbeds [8] provide directions on general testbed management, control and experimentation options but do not give hints on how to evaluate and choose the appropriate hardware tools to build up the testbed.

This paper focuses on providing means for researchers to assess and decide on the hardware to be used when deploying an experimental wireless mesh networking testbed. It elaborates on recent research showing that different vendor solutions offer significant different performance in the lab [5] and that theoretical and simulation results can be discarded too early due to non-correctly calibrated setups [9]. The paper identifies a series of qualitative parameters to be taken into account when deciding on the wireless equipment to be used and proposes quantitative metrics and measurement methodologies to be applied to assess their performance. This serves the purpose of unfolding possible performance limits of the equipment used that must be taken into account during the design process, and revealing possible deviations of the hardware behavior from the theoretical expected one to be accounted for during experimentation.

Specifically, the paper focuses on the hardware solution adopted to build the wireless nodes that compose wireless mesh network testbeds. Previous work has shown that the software tools chosen may also influence the results obtained out of experimentation [10]. In general, though, there is a higher risk that the hardware, not the software, is incorrectly assumed to work as stated by theory, for instance, given its standard compliance claims. The study differentiates two main building blocks of the wireless node, namely, the board (or form factor) and wireless hardware. The board is composed by all those components that are not specific to the wireless transmission process but are generic to any networking platform and, generally, provide the main processing power required to support the networking process. Examples are the processor board, the chassis, the bus, etc. On the other side, wireless hardware refers to those components of the node specifically required to support wireless communications. This includes wireless cards, drivers and RF components that might be used in the wireless node.
The study is presented in two differentiated parts. Firstly, the paper identifies a series of parameters that must be taken into account when devising the wireless node solution adopted (section II). Some detailed description of these parameters is provided in order to show their relevance. Secondly, a series of quantitative measurements are proposed in order to characterize the performance of a specific adopted solution (section III). These measurements serve the purpose of identifying performance limits and unexpected behavioral aspects of the hardware adopted. Section IV illustrates the techniques proposed throughout the paper through various practical examples. Finally, section V concludes the paper.

From a general point of view, the novelty of this paper resides on the fact that it draws the attention on the potential dangers of reaching conclusions without appropriately considering the behavior of the specific hardware in use in the testbed. And more specifically, it tries to establish a framework for helping experimenters in the selection of the appropriate hardware based on both qualitative and quantitative parameters.

II. DESIGN CHOICES TO DEVISE A WIRELESS MESH NETWORKING NODE

This section provides a list and description of qualitative and quantitative parameters to be taken into account when deciding on the hardware to build wireless network nodes. These parameters can be roughly classified into (1) generic parameters and the more specific (2) communications parameters. Firstly, generic parameters refer to those issues that, while defining the performance of the wireless network node, can be encountered in any computing device, regardless of its usage. They mainly refer to computing capabilities. Secondly, communications parameters refer to those related to the process of transmitting data. These parameters can be commonly found in networking literature or be more specific of the radio nature of wireless networking communications.

One might also consider, when differentiating the scope of the parameters, the block division of the wireless node presented in the introduction. The wireless node can be divided into two main parts: the board (or form factor) and the wireless hardware. Taking this into account, one can classify these parameters into one of these three groups: (1) form factor level, (2) wireless level and (3) system level. Form factor level encloses those parameters that determine design choices on the board part of the wireless node. On the contrary, wireless level parameters affect design choices on the wireless hardware to be adopted. Finally, parameters that affect both form factor and wireless hardware decisions as a whole are included under the system level group.

Table 1 provides a list of parameters to be taken into account when designing the wireless network nodes of a wireless mesh network testbed. They are classified according to the part of the wireless node they are related to (system, form factor or wireless level) and whether they are generic parameters or more specific of a communications device.

<table>
<thead>
<tr>
<th>Form factor level</th>
<th>Wireless level</th>
<th>System level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory options</td>
<td>Memory of the device</td>
<td>Power options</td>
</tr>
<tr>
<td>Type of hard drive</td>
<td>Device driver</td>
<td>Interrupt generation and handling</td>
</tr>
<tr>
<td>Operating System</td>
<td></td>
<td>Silent properties</td>
</tr>
<tr>
<td>Bus options and expansion capabilities</td>
<td></td>
<td>Size properties</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transmission power options</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Standard compliance options</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Network interface support options (e.g. multi-interface support)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low level energy measurements (e.g. carrier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Antenna options</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transmission power options</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concurrent handling of incoming and outgoing traffic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Functionality of the node (e.g. active, passive,....)</td>
</tr>
</tbody>
</table>

The rest of this section provides a discussion on the parameters in the table to guide design choices when devising experimental wireless network nodes. As is shown below, in section III, one can assess the performance of devised wireless node solutions by characterizing some of the parameters in this table. These parameters (e.g. forwarding rates) are influenced by decisions taken on a great part of the rest of issues involving wireless node design. The characterization process can be done using simple measurement tools and techniques that reveal whether a design choice adequately matches experimentation requirements. According to the results obtained after an assessment process, design choices might change and different hardware solutions might be proposed for the wireless network node.

**Computational power:** There is available a broad choice of processor families and there is also a wider quantity of processor models with different processing capabilities. Depending on the intended functionality, the software tools to be used and the scope of intended experimentation one should decide on the required processing power. As an example, in order to run non-optimized code, the processor must be powerful enough to support experiments without standing as a performance bottleneck. Therefore, the choice of a processor affects the kind of protocols and applications which can be implemented in the platform, as the node might be limited in computational power. In a wireless mesh testbed, nodes must be able to perform tasks such as forwarding, routing, control, management, and monitoring tasks simultaneously.

**Power options:** In a wireless node, the main power consuming components are, generally, the wireless cards and the hard disks, along with the motherboard itself. Most common wireless devices that can be found nowadays in the
market have a maximum transmission power of 100mW, 200mW and 400mW. Not all the wireless devices can be used in a constrained form factor. As a result and due to power constraints, the mesh node will be limited in wireless support depending on which wireless devices are planned to be used. On the other hand, not only the kind of wireless device to be used is restricted, but also the number of such devices. Moreover, power supply affects the kind of static storage we can use in the platform. We must choose between a small memory flash card with limited size or a big hard disk with plenty of room for data. Finally, power supply needs should be chosen depending on where the wireless mesh node is going to be placed. On one side, a desktop or server PC with a standard A/C power supply with a typical rated wattage range from 200W to 500W is suitable for labs and office environments. On the other side, some embedded boards are limited to a power consumption of 15W. But these boards can be powered directly with DC voltages (e.g. rechargeable batteries or solar cells) and be placed in not-so-standard locations.

**Memory considerations**: Options on the memory system have to be chosen in terms of the type of testbed to be devised. Options range from dummy nodes that PXE boot and rely on remote file systems for data handling to local storage options such as hard drives or flash memory disks. The functionality of the node, the amount of required storage memory and also power consumption issues might determine the choice on the memory options. Additionally, scenarios where fast data collection speed is needed might require, of a fast access memory system in order not to loose data. RAM memory might help in short term experimentation but more complex solutions might be devised when long term experimentation (and data collection) takes place. Besides, one might also take into account the **memory of the device**. Depending on the type, nature and congestion level to be supported during experimentation, some devices might not have sufficient space or flexibility to behave appropriately. Most WLAN devices, for example, allow modifying the amount of device memory allocated for outgoing information (generally specified in number of packets) but, traditionally, this is less than a dozen of packets.

**Interrupt generation and handling**: The way interrupts are generated and handled influences several performance characteristics of a node. Among others, examples of such performance characteristics are: packet timestamping in monitoring nodes, forwarding rates at router nodes, concurrent traffic handling at nodes in collaborative multi-hop networks [11], supported loads, etc. Interrupts can be generated (and handled) per each event, per group of events (batch attention) or just be disconnected and set the system to rely on polling mechanisms. Modern OSs support hardware polling options in order to improve networking efficiency in highly congested environments [12]. Besides, real-time solutions or even hardware driven solutions [13] are adopted to overcome interrupt driven limitations. Correctly assessing and tuning wireless nodes with respect to this issue may sensibly improve accuracy of experimentation results.

**Bus options and expansion capabilities**: There is a broad spectrum of bus types and options in the computing world. However, typically wireless device packages support only a few, namely PCI, PCMCIA, mini-PCI, USB or even Ethernet ports. Options, in this sense, when choosing the form factor to be used, affect the type and quantity of devices -mainly the wireless devices- which can be added to the hardware platform. There are some popular more powerful buses, for instance the new PCI Express bus. But for the time being, however, there are not many available wireless devices supporting this type of bus. Nowadays, bus transfer capacity is never considered a bottleneck for wireless networking, even in multi-radio scenarios or when using new technologies that support higher bit rates such as the MIMO 802.11n standard. In some cases bus expansion solutions must be considered to connect more than one device to a board that has a single bus interface slot. There exists, for example, multi mini-PCI-to-single-PCl adapters. However, care must be taken with respect to the increase in power consumption that this option represents in order not to burn the board circuitry.

**Standard compliance options**: There are a number of wireless technologies that can be considered to be used in a wireless mesh networking testbed. However, typically, IEEE 802.11 WLAN based devices are used. Reasons for this might be, among others, the suitability of this technology for outdoor, indoor, short and mid-range communications, the permanent activity of its standardization body in order to accommodate new physical and link layer technologies, the availability of several off-the-shelf hardware solutions and the extended platform support of drivers and control software. Depending on the design choices, one might consider using new products supporting extensions of the 802.11 protocol such as the 802.11e for QoS at the link layer and 802.11n for MIMO transmissions. One might also choose alternative technologies that might better suite the research task. Besides, when choosing the wireless hardware to be used one might also consider the flexibility that this hardware offers in order to overcome standard specifications, ore even which is the degree of standard compliance that the hardware offers. It has been shown (see [5] and [6]) that not all the devices behave comparably when interacting with other devices, even though they support the same standard specification.

**Devices, device drivers and functionality options**: Most of the available WLAN products are based on some few OEM designs and, typically, WLAN cards are differentiated using their chipset name. The popularity of these chipsets has changed during the last few years depending on several factors such as the performance offered, the standard supported (802.11b, 802.11a,...), their market availability and the operating system (OS) support. When designing a wireless mesh node, however, additional technical aspects must be taken into account to evaluate the proper wireless device to be used. On one side, not all driver, firmware and devices support all functionalities. These functionalities might be standard specified ones such as access point, ad hoc, client or other de facto established ones such as the sniffier functionality. Care
must be taken when deciding on the wireless hardware so that it supports the functionality required and behaves as expected. While there exist an extended literature on WLAN devices and support, when using other wireless technologies special interest must be placed on system support options and flexibility to make sure that the experimentation planned is possible.

**Multi-radio options:** Multi-radio requires an important effort on calibration and assessment of the wireless node setup. Potential interference between wireless devices must be controlled or taken into account in experiment results. The study in [6] provides some hints on how to assess the multi-radio performance of a node. Solutions such as assuring correct impedance matching of components, separating antennas of devices or placing attenuators between the antenna and the wireless NIC itself are possible solutions that can be adopted to minimize inter-device interference in multi-radio settings.

**Transmission power options:** Recent research [14] has shown that care should be taken when choosing wireless hardware solutions as they might not support control over transmission power options. Besides, depending on the nature of the experiments and the number of wireless nodes that are planned to be spread, researchers might also consider obtaining hardware from different regions applying different control rules. As an example, one might consider for example that the US regulation allows transmissions of up to 1W to WLAN devices while European regulations restrict this power transmissions to 100mW.

**Antenna options:** Multi-radio based mesh nodes must be able to accommodate more than one antenna. However, at the same time, antennas have shown to be the most important source of inter-device interference in multi-radio settings (see [6] or [9]). Engineering solutions must be adopted to reduce this effect such as antenna separation or signal attenuation. The wireless node must be able to accommodate these kind of solutions. Besides, if one is planning to use external antennas the wireless devices used must have an external antenna connector. This is a common situation for mini-PCI or PCI based wireless devices but not in USB or PCMCIA based wireless devices. Finally, options for antennas also include using sectorized antennas. The researcher, however, must take into account that sectorization is only effective in outdoor environments where, depending on how these measurements are done, a variable number of hidden stations can appear and compromise transmissions. The experimenter would rather use wireless hardware offering the possibility to adjust energy measurements and processing. This allows for a wider range of network deployment options to conduct experimentation.

Section III elaborates on how to quantitatively measure the performance of a wireless device when conducting energy measurements.

**Networking properties:** There are a number of characteristics that, classically, define the performance of a networking node that can be also applied to a wireless mesh node. Additionally, here we list also some other ways to characterize the performance of a node that have recently been used in the literature and that are more specific to wireless networking nodes. In this way, knowing the forwarding rates (for small and large message passing) and traffic generation and reception capabilities are important to assess the performance of a devised node. These values are typically influenced by some of the other parameters present in Table I such as the processor, bus interfaces and storage capacity. Additionally, the performance of a node when handling concurrent incoming and outgoing traffic should also be characterized. Nodes in a wireless mesh network might either act as relays of traffic and/or as traffic generators (or collectors) and have to be capable of combining both sending and receiving concurrently without a penalty in the performance. Section III further elaborates on these characteristics of a wireless mesh node and presents measurement methodologies to obtain them. Interestingly enough the values for these parameters are mostly determined by the design choices made on most of the rest of parameters that have been described in this section. Through the characterization of a wireless node with respect of these properties, decisions can be raised on the adequateness of the decisions taken on the rest of parameters

**Silent properties and size:** Other features that might determine testbed design are the silent properties of the solution devised and the size of the final node. Installing nodes in an office environment, for example, should take care of not annoying workers with an excessive noise level. At the same time, depending on the location planned for the nodes, not all case sizes fit the location requirements.

### III. PERFORMANCE ASSESSMENT OF A DESIGNED WIRELESS MESH NETWORKING NODE

Once design choices have been taken with respect to the options listed in section II, a quantitative performance assessment of the hardware chosen should be conducted. This performance assessment would serve the purpose of validating the design choice that has been picked out and finding possible deviations of the hardware performance from the theoretically expected ones. The output of the assessment study should be then taken into account both while designing the experiment and when analyzing final results.

The following subsections propose a series of recommended practices (section III.A) and measurement techniques (section III.B) to characterize the behavior of a designed wireless node and to identify possible performance limitations or unexpected behavioral aspects.
A. Recommended practices when characterizing hardware

There follows a list of recommended practices when characterizing the performance of an experimental wireless node. This list builds on our own experience dealing with performance assessment and characterization of wireless nodes and does not claim to be neither an exhaustive nor a closed list of steps to follow by experimenters.

1) Whenever possible, start first by characterizing and deciding on the wireless hardware to use

While building a wireless mesh node one can use either customized or commercial off-the-shelf products. However, the distinction between the board and the wireless hardware is still valid. Depending on the solution adopted, however, it might be possible to obtain a separate characterization of the wireless hardware prior to characterizing the wireless node as a whole.

This is not possible when standalone platforms, such as commercial mesh routers, are packaged with the wireless devices embedded in the platform. However, such separation is possible when the wireless node is built using a regular computer with commercial wireless devices attached to it. Due to the availability of such products and its cost-effectiveness, this has become a common practice in current experimental wireless networking.

Recent research has shown, however, ([5] or [6]) that not all wireless hardware solutions behave comparably, regardless of the board functionality, and it is an interesting practice to characterize the devices to be used prior to building the wireless node itself. This serves also to identify or discard possible wireless hardware related bottlenecks when analyzing the whole node performance.

Separate characterization of the wireless hardware can be done by using a Low entry server as the form factor support in order to assure that processing power of the board is not the limiting factor. Wireless hardware would be typically characterized by obtaining (1) traffic generation and reception rates, (2) possible concurrent traffic handling limitations and whenever possible (e.g. IEEE 802.11 devices), accuracy of low level energy measurements.

2) Check and tune the operational characteristics of devices and components

Conscious tuning of the devices used should be always conducted, even more during the characterization process. Among other issues, attention should be paid on the following ones. Firstly, (1) choose appropriately adapted RF components to your working frequency. Commonly, the higher the working frequency the more cautionary one should be. Secondly, (2) devise an appropriate data gathering methodology. Issues such as hard drive writing access delay or speed might compromise data collection. Third, (3) the maximum bus transfer speed and processor power should always be taken into account when evaluating results. Finally, (4) some drivers offer configuration options that are not really implemented in the wireless hardware that they control. Double check this before starting measurements.

3) Whenever possible, use cables, otherwise, avoid interferences and gather measurements using close LoS communications

Performance characterization of the hardware used should be done in the absence of complex propagation losses. The objective here is characterizing the hardware used regardless of the environment.

RF cables are a very convenient solution to conduct measurements. Devices are both isolated from external interferences and safe from unintended propagation losses. However, not all wireless hardware solutions offer the possibility to connect cables or external antennas. In these cases, wireless nodes that establish a communication during any test run should be placed close to each other and within Line of Sight in order to minimize unintended propagation effects. Experimental runs show that either using cables or close LoS communications (in the absence of external interferences) show close results even in indoor environments [7].

4) Bear in mind that single-radio performance upper-bounds multi-radio performance

Unlike the previous practices, which dealt with the preparation of the setup, this one is more related to the interpretation of results obtained over a certain setup.

In fact, and as was shown in [7], the performance of a single-radio setting upper-bounds the performance of the same device in a multi-radio setting. This can be used as a reference when calibrating multi-radio nodes. The closer the performance of the multi-radio node is to the multiple single-radio case, the better calibrated your setting is.

B. Quantitative measurement techniques

Once the above practices are followed, the experimenter is able to measure and quantitatively analyze the hardware used. The basic metric to be measured in order to assess the performance of the designed wireless nodes is the supported workload. This is generic to any computing system but, when particularized to networking devices, it translates into analyzing the network traffic load supported by the hardware that is going to be used. Traffic load analysis can take many forms and can be measured in distinct ways, some of which are proposed here.

Besides, one might also take into account that, as pointed out before, the wireless node is composed of two differentiated parts: the board (or form factor) and the wireless hardware. One should devise assessment methods able to separately characterize their performance in order to better identify the source of possible limitations or misbehaviors.

A series of common setups and proposed techniques to analyze the performance of a wireless networking node are listed and described in this subsection. The focus is on those parameters of Table 1 that may be quantified. Each one of these techniques is influenced by one or some of the design choices taken with respect to the parameters listed in the previous section.
1) Traffic generation and reception capabilities

This proposed measurement methodology aims at obtaining the maximum rate at which a node can generate or receive traffic without dropping packets. Figure 1 shows the reference setup to characterize the traffic generation and reception capabilities of a wireless node design (NUT in the figure). The tester node in the figure should be a node that has been previously characterized or that is over-dimensioned with respect to the NUT.

![Figure 1](image1.png)

**Figure 1.** Reference setup to obtain (a) traffic generation and (b) traffic reception capabilities of a node under test (NUT)

The measurement procedure to characterize traffic generation capabilities consists in the following. The wireless node (NUT in the figure) is set to generate a traffic flow with specific packet rate and packet size characteristics. The tester node is set at the same time to collect this traffic flow and measure the packet rate at which it receives the flow. After that, the packet rate to be sent is increased and the same test is repeated. This same procedure is repeated until the flow eventually reaches saturation and it cannot generate the packet rate it is requested to. In order to analyze packet reception capabilities the tester node and the NUT are just inter-changed and the same procedure is repeated until the NUT starts dropping packets or transmission bounds (determined by the technology used) are reached.

The wireless node is characterized by obtaining the relation between the traffic load that it is requested to send (or collect) and the actual traffic that it sends (or collects). Typically a wireless node, when generating traffic, should be able to reach (and not surpass) the traffic bounds imposed by the standard specification that it follows (see [17]).

A series of factors, however, may affect and limit the performance of a node with respect to this measurement. Among them, one can list: the processing power of the form factor or the wireless device itself, the maximum storage capacity of the wireless hardware, the interrupt handling process in the inter-communication between the device and the board, the degree of standard and protocol compliance of the wireless devices, the (in)correct calibration of the wireless node and the interaction between different hardware components that interfere one to each other. This analysis has been applied in [5] and [7] in order to characterize the performance of commercial wireless hardware.

2) Forwarding rates

This is a classic benchmarking technique, commonly applied to switching and routing nodes [15]. It accounts for the number of frames per second that a node can send to the intended destination in response to an offered load. Figure 2 shows the reference setup used to obtain the forwarding rate characterization of a wireless node (NUT in the figure). Again the tester must be either a well calibrated node or an over-dimensioned node with respect to the node.

![Figure 2](image2.png)

**Figure 2.** Reference setup to characterize the forwarding rates response of a node under test (NUT)

The procedure consists in generating traffic from one tester that the wireless node being assessed must forward to the other tester. Comparing the packet rate received at the receiving tester with that generated at the sending tester characterizes the forwarding rate response of the NUT.

A part from the factors listed above that might be shaping the traffic generation and reception capabilities of the wireless node, there are a number of additional issues to be taken into account here that also determine the forwarding rate performance of the node. First, when a single wireless interface is used for forwarding, the forwarding rate might be limited when higher priority is given either to the sent or received traffic. An example of such situation would be a case when the mesh node is relaying traffic between two nodes that cannot see each other but that are working at the same frequency channel. Second, when multiple networking interfaces are considered (i.e. wireless interfaces), considerations such as the mutual interference among them and the power consumption requirements might also be important limiting factors.

3) Concurrent traffic handling

This proposed measurement methodology comes out from the observation that at any time, wireless mesh nodes, might be not only forwarding traffic from other stations but also generating and/or collecting traffic themselves. This can be thought as joining together the forwarding rate measurements and traffic generation and reception capabilities. The measurement technique aims at determining what is the traffic load that a station is able to reliably handle when it is dealing with both incoming and outgoing traffic concurrently. Reliable here means that no packet drops are observed neither in the incoming, nor the outgoing traffic of the measured wireless node. This technique was first proposed in [11] and Figure 3 shows a reference setup that can be used to characterize this property of a wireless node.

The measurement procedure consists in starting two concurrent flows, one originates in one of the tester nodes and the other in the wireless node being tested. Both flows are identical and the packet rate is progressively augmented while conducting measurements.

![Figure 3](image3.png)

**Figure 3.** Reference setup to characterize the concurrent traffic handling capacity of a node under test (NUT)

The characterization consists in obtaining the relation between the rate of packets collected at the wireless node (from
flow 1 in the figure) with the number of packets generated by the wireless node (flow 2 in the figure). In case there exists a point where the wireless node starts loosing packets (either received or send) the measurement presents a mismatch between the rate of packets collected and generated. Characterizing the wireless node with respect to this parameter consists in finding the maximum sustainable traffic (incoming and outgoing simultaneously) without suffering loss.

The same factors shaping the forwarding rate capabilities of a node, determine this characterization. In fact concurrent traffic handling capacity generally lower-bounds forwarding rate capabilities. Depending on the intended functionality of the node one or the other characterization is preferable.

4) Carrier sense measurements accuracy

This measurement methodology aims at characterizing the accuracy of a node when gathering low level energy measurements. The presented methodology was proposed in [11] and is specific to IEEE 802.11 WLAN based nodes.

Some wireless vendors allow the possibility to adjust the method with which carrier sense measurements are conducted. However when low level energy measurements are not precise enough the experimenter might consider changing the hardware choice.

5) Power consumption

When the planned wireless mesh networking testbed relies on battery powered wireless nodes (e.g. the nodes are to be deployed as standalone units in an open-field environment), power consumption characterization measurements are a must. These measurements may help controlling battery lifetime and plan a battery swapping strategy without affecting overall experiment performance.

The measurement methodology basically consists in using a programmable DC power supply to power the board that we intend to use, perform various regular operations with the wireless node and measure the current and power consumed. We propose here some basic analysis tests to run when assessing the power consumption of a multi-radio wireless node. One would measure the power consumption when: (1) the board is halted but does not carry any wireless device, (2) the board is booting without carrying any wireless device, (3) the board is halted carrying all wireless devices, (4) the board is booting with all wireless devices in it, (5) the board with all devices is in standby mode, (6) the wireless node is in active mode using all wireless devices.

Depending on the intended use of the node and its configuration this list might change or be extended to cover all the expected operational cases. Note also that when using laboratory programmable DC power supplies, the maximum current to be supplied should be limited in order not to burn any component of the wireless node being assessed.

IV. GOING PRACTICAL: ILLUSTRATIVE CHARACTERIZATION OF REAL HARDWARE

This section provides an example of how to put into practice the techniques described in the previous section and the type of results obtained in order to assess the convenience of the hardware to be used to build a practical wireless mesh networking testbed.

In order to build the EXTREME mesh testbed, a laboratory testbed designed within the IST WIP project [16], we have conducted an extensive hardware characterization campaign. Some of the most illustrative results are presented here in order to show the concepts described all along the paper.

Firstly, we present some examples and results on the characterization of different WLAN hardware options considered for the testbed. Secondly, we present also some results on the characterization of different form factor options that were considered for the testbed. As mentioned, stress is put on finding illustrative examples of the characterization process rather than showing the best design choice option, as the latter highly depends on the particular requirements of a given setup. As an example, we present an extended characterization of the Soekris Embedded Board (net4801).
A. Quantitative characterization of wireless hardware

This section is based on the results presented in ([5], [7] and [11]) from which we have selected some illustrative examples.

As mentioned before, in order to isolate the effects of the wireless devices from any form factor limitations, we use low entry servers to carry wireless devices. The low entry server is over-dimensioned (e.g. in terms of computational power or bus capacity) with respect to the networking requirements, which assures that board capabilities do not represent a bottleneck for the wireless networking task. Tests with gigabit Ethernet cards have confirmed this overdimensioning.

1) Traffic generation and reception capabilities of wireless devices: single and multi-radio

This parameter has been classified as system level in Table 1. However, the overdimensioning of the server used in the tests allows focusing on the bottlenecks coming from wireless devices.

Figure 5 plots the characterization of the traffic rate capabilities when applying the measurement technique explained above in section III.B. The (unicast) traffic rate actually generated (and collected) is plotted versus the traffic rate requested. The units of the values presented are packets per second and the packets sent have an application payload length of 64 bytes.

![Figure 5](image)

**Figure 5.** Relation between packet generation rate requested and the actual performance for various AP-client pairs

The characterization is obtained for a series of different types of popular wireless hardware pairs. The figure shows how depending on the hardware device that we are using at the sender or the receiver side, different traffic rates are achieved. This difference is related to the way that each one of the devices (and device driver configuration) follows the standard protocol specification. More details can be found in [5], but some results on the maximum rates achieved in each case are summarized in Table 2. This shows how not all hardware following the same standard specification presents the same results. This allows concluding that tests should be conducted prior to the experimentation task in order to understand the behavior of the hardware used.

### Table 2. Maximum packet rates for different hardware pairs

<table>
<thead>
<tr>
<th>AP Client</th>
<th>Phy std/txrate</th>
<th>Max packet rate achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atheros Atheros</td>
<td>802.11b/11Mbps</td>
<td>~2900pps</td>
</tr>
<tr>
<td>Atheros Prism</td>
<td>802.11b/11Mbps</td>
<td>~1845pps</td>
</tr>
<tr>
<td>Prism Atheros</td>
<td>802.11b/11Mbps</td>
<td>~1238pps</td>
</tr>
<tr>
<td>Prism Prism</td>
<td>802.11b/11Mbps</td>
<td>~1238pps</td>
</tr>
<tr>
<td>Cisco-AP1200 Atheros</td>
<td>802.11b/11Mbps</td>
<td>~2497pps</td>
</tr>
<tr>
<td>Cisco-AP1200 Prism</td>
<td>802.11b/11Mbps</td>
<td>~1465pps</td>
</tr>
</tbody>
</table>

Figure 6 plots the results obtained when analyzing the traffic rate capabilities of a multi-radio node. The curve characterizes the resulting aggregated rate when a three-radio multi-radio node communicates with three independent single-radio nodes. Each link is established in an orthogonal channel and all radios (in the multi-radio node and the rest of single-radio nodes) are based on an Atheros chipset. Additionally, the figure includes, as a reference, the resulting rate aggregation when all communications are established using single radio nodes both at the sender and receiver side. The figure shows how: (1) the multiple single-radio node case upper-bounds the performance of a single multiple-radio node, (2) non-correct adaptation of RF components causes performance degradation, and (3) incorrect antenna separation and placement also degrades the performance of the multi-radio node. More details and additional results can be found in [7]. This shows how devices should not only be characterized in single-radio settings but also in multi-radio settings prior to taking a decision.

![Figure 6](image)

**Figure 6.** Performance in transmission of a multi-radio node based on Atheros devices transmitting in orthogonal channels

### 2) Carrier sense measurements accuracy

Figure 7 plots the characterization curve presented above in section III.B to assess the accuracy of a wireless device based on the Prism chipset with respect to the carrier sense measurements. As explained above, the results fall between an upper and lower bound (the shadowed region in Figure 4), indicating that, with this configuration, the wireless node handles incoming and outgoing traffic correctly and the measure, then, can be confidently used to compute the accuracy on the carrier sensing task. An accuracy factor of 0.89 is obtained. A more detailed explanation can be found in [11].
B. Quantitative characterization of form factor

Once the wireless hardware to be used has been characterized, the wireless node (form factor and wireless hardware) can be analyzed as a whole. The previous wireless hardware characterization helps, then, in identifying possible performance bottlenecks when analyzing the results of the assessment tests.

1) Power consumption

Table 3 summarizes the power consumption values obtained for a Soekris Embedded Board (net4801) when one applies the measurement procedure described in section III.B. The Agilent Programmable Power Supply E3646A was used to obtain the values of current and power consumption. It is set to provide a voltage of 12V and the maximum provided current is limited to 1.4A in order to avoid burning the board. In those specified cases, 3 wireless mini-PCI Atheros cards are connected through a mini-PCI-to-PCI adaptor. One can notice that even when the board is halted the cards continue draining some current. One can see that the board almost reaches the limit (maximum current supported by a PCI bus) when it is set to start some activity (case 6 in the table). This compromises the usage of this kind of board in multi-radio mesh settings, as there is a high risk of burning the board and, due to its high power consumption, battery lifetime is low.

Table 3. Power consumption analysis for a soekris board

<table>
<thead>
<tr>
<th>Performed Tests</th>
<th>Maximum Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in Amps</td>
</tr>
<tr>
<td>1 Halted w/o any card</td>
<td>0.38</td>
</tr>
<tr>
<td>2 OS Booting w/o any card</td>
<td>0.71</td>
</tr>
<tr>
<td>3 Halted w/ 3 wireless cards</td>
<td>0.46</td>
</tr>
<tr>
<td>4 OS Booting w/ 3 wireless cards</td>
<td>0.74</td>
</tr>
<tr>
<td>5 Standby</td>
<td>0.86</td>
</tr>
<tr>
<td>6 Wireless and hard disk activity</td>
<td>1.10</td>
</tr>
</tbody>
</table>

2) Forwarding rates

Figure 8 plots the results when characterizing the forwarding rates of a Soekris Embedded Board (net4801). The test setup consists in the following. Two Low entry servers (A and B) communicate through a wireless mesh router consisting in the Soekris board carrying two Atheros based mini-PCI wireless devices (specifically, they carry Wistron CM9 802.11a/b/g cards). The Servers are also carrying the same wireless cards, so that two wireless links are established: one from one server to the Soekris board and the other from the Soekris board to the second server. To avoid interferences between them, they are set to two 802.11a orthogonal channels. Flows are generated using the MGEn traffic generation tool and cards are configured to work at 54Mbps physical rate.

Figure 8. Forwarding rate supported by a Soekris net4801 board carrying two Atheros based mini-PCI cards.

The figure shows how for low size packets the performance of the node reaches an upper-limit after which there appears performance degradation. The source of this degradation is not the wireless hardware used. As shown in Figure 6, multiple Atheros devices, when correctly placed and tuned, can coexist in a single node without suffering performance degradation. The characterization process shows that the Soekris board presents some performance limitations that should be taken into account when designing experiments. It is worth noticing here that forwarding rates achieved differ depending on the direction (the source node) of the UDP flow. Our observations suggest that the performance of the board changes depending on the receiving and forwarding card used (depending on the slot in which they are placed).

Figure 9. Forwarding rate supported by a mini-ITX board carrying two Atheros based mini-PCI cards.

As a proof-of-concept, we repeat exactly the same experimentation using a mini-ITX board and show (see Figure
9) how there is no degradation of performance and forwarding rates achieved correspond to those offered by the wireless devices used.

3) Traffic generation and reception capabilities

Once traffic generation and reception capabilities for the wireless hardware have been characterized, similar tests should be conducted, but with the complete wireless node set up. Figure 10 shows the generation rate performance of the Soekris Embedded Board (net4801) carrying two Atheros based cards. The wireless node is set to send two UDP flows that sink in two independent single-radio nodes. One might observe that the performance degradation already appears at 1000 packets per second, which is below the performance limitations of the wireless hardware.

Figure 10. Performance in transmission of a Soekris board sending two UDP streams using two different cards in orthogonal channels.

V. CONCLUSIONS

From a general point of view, the novelty of this paper resides on the fact that it draws the attention on the potential dangers of reaching conclusions without appropriately considering the behavior of the specific hardware in use in the testbed. And more specifically, it tries to establish a framework for helping experimenters in the assessment and selection of the appropriate hardware. In this sense, it presents a list of qualitative and quantitative parameters to take into account when making design choices on how to build the wireless nodes that compose the wireless mesh network. Additionally, the paper presents a series of measurement techniques and recommended practices to assess the performance of the wireless nodes designed. Correctly assessing the performance of the wireless node serves the purpose of unfolding possible performance limits of the equipment used that must be taken into account during the design process, and revealing possible deviations of the hardware behavior from the theoretical expected one to be accounted for during experimentation.

ACKNOWLEDGMENTS

This work was supported in part by the European Commission project WIP under contract 27402 and by Generalitat de Catalunya under grant number SGR2005-00690 (Grup de Recerca Singular).

REFERENCES


