Low Consumption Home Femto Base Stations

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***Abstract*— The expected massive adoption of home femto base stations will increase the overall power consumption, requiring eco-designed sleep modes. Whenever there are no user under the coverage of a home femto base station (at night for example), keeping it on can be seen as a waste of power, excessive interferences and lack of security. This paper proposes a method to switch-off the femto base station radio emission and wake it up when necessary. Our approach uses a second low-power channel that carries out-of-band control information to maintain connectivity. The paper will provide the software and hardware architecture and performance results of a Wi-Fi demonstrator.**

Energy saving, femtocell, sleep mode, low-power consumption, sensor networks, reverse paging, Wi-Fi

I. Introduction

With the current international focus on climate change issues, energy management will be at the center of eco-sustainability initiatives adopted by telecommunication industry actors. This study focuses on reducing the carbon footprint of home femto base stations. These user-installed equipments are expected to be extensively deployed, introducing significant additional energy consumption. Recent European directives [1] required to include eco-designed off-mode or standby-mode in the household and office equipment. By the end of 2012, the equipment will have to automatically switch to off/stand-by mode after a short period of inactivity. Furthermore, the energy consumption limits of those low-power modes are set to be challenging.

In this paper, we have chosen Wi-Fi technology to demonstrate our idea of implementing a low power-sleep mode that could be further extended to any femtocell technology in the scope of the Femto Forum [2]. We focus on home indoor Wi-Fi Access Points in infrastructure mode. Today, Wi-Fi Access Points (AP) are always consuming a relatively significant amount of energy as they have to periodically broadcast special beacons to signal their presence to the clients. This beaconing is mandatory in the 802.11 standard [8]. It means that the radio module is turned on as longer as the AP is on. Furthermore, even in idle state (i.e. mostly in receive mode except for beacons), AP consumes relatively high amount of energy. This is due to the low energy efficiency that is typical for the RF front end. Whenever there are no users under the coverage of an AP, at night for example, this can be seen as a waste of power, lack of security, and human exposition to useless radiation.

In this context, the technical problem addressed in this paper is how to save energy by switching entirely off the 802.11 interface of the AP, while still being able to serve a user request for a connection. To tackle this issue, we use low-power properties of radios designed for sensor networks. In our case those radios carry out-of-band control information to maintain connectivity and wake up the AP when necessary. We have set-up a demonstrator of this low-consumption Wi-Fi system.

The rest of the paper is organized as follows. In Section II we will present the related work. Then in Section III and Section IV the design and the implementation of the hardware and software architectures of the low-power system are described respectively. The system performances are detailed in Section V giving energy saving amounts and wake-up delays results for our Wi-Fi prototype. The conclusions and future plans are discussed in the last Section (VI).

II. Related Work

The low-power-wake-up concept has already been studied in the context of sensor networks [3][4] as the optimization of battery lifetime is a critical issue for sensor nodes.

For user mobile handsets, the similar idea of using a secondary out-of-band mechanism to remotely activate a user terminal using passive, low-power but short range RF ID tags was theoretically studied in [5]. The closest to our approach can be found in [6], where they use custom-designed low-power radio modules to wake up battery powered-devices like Personal Digital Assistants (PDAs). While using similar technique, the goal in that paper is completely different – saving power on mobile terminals. While important, we consider that goal well achievable by the standard means provided by the 802.11 standard, and thus, the higher price paid by introducing additional radio is not justified. On contrary, our method is aimed at power savings in Wi-Fi APs, which cannot be achieved without introducing the extra radio. Furthermore, we don't use custom made low-power radio module, but one that is well-established and that has huge software support. In this way, well known and tested complex MAC protocols for the low-power radio can be immediately put in place. Those protocols will be necessary for end-user industrial implementation of our approach.

For cellular access networks, Chiaraviglio et al. showed in [7] that a large amount of energy can be saved if an optimal dynamic radio coverage planning is used instead of a static one for an UMTS access network. In particular, they switched off some cells in urban areas during low-traffic periods. Unlike our paper, they deal with outdoor macro base station and provide analytical and simulated results, whereas we are focusing on indoor Wi-Fi Access Points. We have designed an actual implementation of a real system, using ultra-low-power radios traditionally employed in sensor networks.

III. ARCHITECTURE

We add an auxiliary low-power radio link, and thus a new out-of-band channel, to turn on the Wi-Fi interface.

The principle of the prototype is shown on Fig. 1.

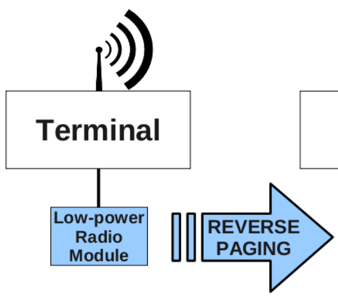

Figure 1. Overall architecture of our proposal

At each side of the Wi-Fi link (Terminal and Access Point), there is a low-power radio module in addition to the Wi-Fi radio, with which extra radio out-of-band control information is carried out. This information is transmitted only from the terminal to the Access Point when the user needs an internet connection. Note that the low-power radio operates at different frequency and uses different MAC protocol compared to the Wi-Fi.

There are two basic criteria involved in the proposed solution:

- **“Reverse paging” to wake up the AP.** Every time the user launches an application which require an internet connection, the related low-power radio transmits a paging message to the AP to signal its presence. The low-power radio module connected to the AP receives that signal, it checks user permissions and wakes up the AP if the user can be authenticated. In case the user already has an active internet connection, no reverse paging messages are sent.
- **Check of the active connections to maintain the AP awake**. The AP controller checks the presence of active network connections belonging to the Wi-Fi interface. If any connections are found (meaning that potentially there are active users) the Wi-Fi is kept on. If no active connections are found the AP turns off the Wi-Fi interface.

When the second criterion is satisfied the reverse paging becomes redundant: therefore, the low-power radio module at the AP side can be set in sleep mode.

The different expressions like “turn on” or “wake up” refer exclusively to the Wi-Fi part of the AP, the power supply of the other components remains on as long as the AP is on. It should be noted that the criteria mentioned above are very flexible, and can be modified or augmented according to user needs or configuration without any problem (For example PC boot could trigger the terminal-side low-power radio module to perform a first handshaking procedure with the AP).

In the case of a commercial system and of an encrypted Wi-Fi connection (i.e. restricted access system) the low-power radio connection should be secured too. However, the implementation of an encryption scheme for the low-power radio messages goes out of the scope of this paper.

IV. IMPLEMENTATION

We describe the components of the prototype below:

The Linksys WRT54G v3.1 has been chosen to be the Access Point in our testbed. The selection of this model has been based on decision criteria such as the capability to run open source firmware and the amount of available on-line documentation. Those criteria were established taking into account the need to modify the behavior of the device and to integrate the low-power radio module.

The terminal used in the simulations is the laptop Lenovo T400 Core2Duo P8400@2.26GHz, it incorporates an INTEL® Wi-Fi Link 5100 AGN wireless interface. Debian Linux runs on the terminal, and the driver used for the wireless card is IPW2200.

As low-power consumption module, we have chosen the TinyNode 184 [11] which is a state of the art ultra-low-power module that provides a simple and reliable way to add wireless communication to sensors, actuators, and controllers. It uses a Semtech SX1211 radio transceiver that can operate in the 868-870Mhz license-free ISM (Industry Scientific and Medical) frequency bands. This device fulfilled our requirements to have a transmission range similar to the coverage range of the Wi-Fi AP, and also permitted to have a wake-up signal that contains an identifier in order to avoid unnecessary wake-ups.

TABLE I. TINYNODE 184-MAIN FEATURES

Power consumption	TX mode: 15/25 mA (0/10 dBm) RX mode: 3 mA Stand-by mode: 4 µA
Power supply	1.8 - 3.6 V
Transmission range	Outdoor 150 m @ 25 kbps +10dBm Indoor 50 m @ 25 kbps +10dBm
Firmware	TinyOS

A. Hardware

In order to shutdown the Wi-Fi interface on the AP, we exploit a feature of its Broadcom chipset. By issuing a special command the chipset can completely power down the Wi-Fi radio.

Fig. 2 depicts our modification to the AP.

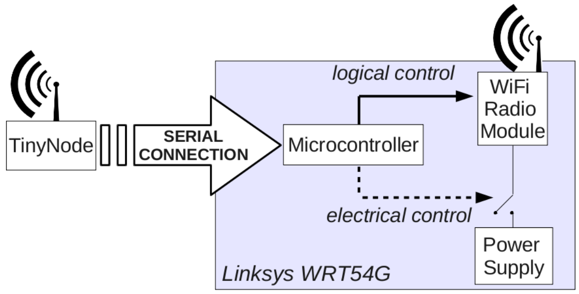

Figure 2. Modifications to the Linksys WRT54G AP

The communication between the low-power radio module and the microcontroller of the AP is done via serial connection. The low-power radio is supplied directly from a 3.3V line of the AP.

On the terminal side the TinyNode is placed on its Extension Board and is connected via a Serial-to-USB converter to the Lenovo laptop. At the machine, the Linux kernel sees logically the link to the low-power module as a serial connection.

B. Software

In order to implement the sleep mode and the wake-up process of the AP, we developed software modules for terminal, TinyNode low-power radio modules, and Access Point. Fig. 3 summarizes the software end-to-end implementation of our reverse paging solution.

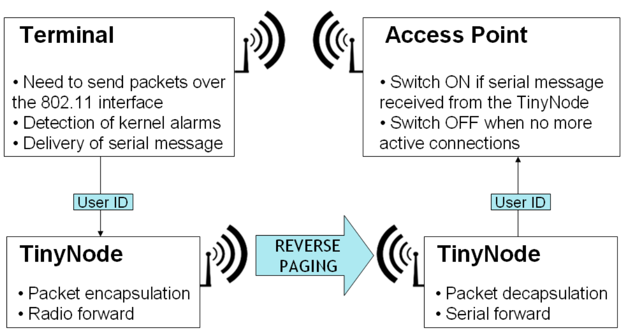

Figure 3. Global interaction view of the software developed

The software running on the low-power modules has been developed under TinyOS in NesC language, please refer to [9] for further details.

Below follows a description of the software modules that were developed:

C. Terminal module

Whenever an application, running at terminal side, needs an Internet connection, the system has to wake up the access point it wants to associate with.

Every application that require an Internet connection, e.g. Browsers or VoIP clients, drive the OS to create IP packets. If there are no active Internet connections the kernel will generate error flags to signal that there have been problems while trying to send data over the net. This holds also when one launches a new application and there is no Internet connection.

Under a Debian environment, we have implemented an algorithm to signal the TinyNode about any packet that cannot be delivered by the kernel. Exploiting the virtual files which monitor the network status and track kernel events, our software transmits serial messages to the low-power radio when the kernel does not succeed to send a packet over the 802.11 interface. At each error that generates one of the above alarms, the application will deliver a serial message containing user's identification information (labeled as User ID in Fig. 3).

D. "TinyNode at the Terminal" module

In this configuration the TinyNode sends reverse paging in the case serial messages have been recently collected and there is no active Internet connection. After one periodic timer expiration, the software will check the serial buffer, pick the payload up (of the 1st message if present) and forward it on the radio interface. As mentioned above the serial message payload is labeled as User ID in Fig. 3. TinyOS provides the Active Message (AM) layer to create AM radio packets which can be used to set a destination address and a data type. Since our purpose is to wake up a potentially unknown access point, we will deliver radio packets setting a broadcast address.

E. "TinyNode at the Access Point" module

At the AP side, we exploit the event handler feature. Indeed, every time a radio message has been received, a task will deliver a serial message toward the AP. This can be seen as an asynchronous alarm.

The procedure activated by this alarm will take out the radio packet payload, i.e. User ID, and forward it over the serial connection described in Fig. 2 to the AP microcontroller. Serial messages are stream oriented, this means that we are not building a structured serial packet but we are sending streams of simple bytes.

F. Access Point module

The software has been developed under OpenWrt [10]. Since it supports add-on packages, we have created a specific package which has to handle the auxiliary signals coming from the TinyNode, check the user activity, and consequently drive the Wi-Fi interface.

The algorithm turns the AP's Wi-Fi interface on if it receives serial messages from its TinyNode. It then keeps it on until there are open connections with users under the Wi-Fi coverage. An open connection can be identified by exploiting the state machine within IP tables. The application checks the virtual file in charge of tracking sessions: it filters the connections belonging to the Wi-Fi interface (defined under a different IP subnetwork). Those entries are related to a TTL (Time To Live): one can exploit this feature to give the user an inactivity margin. Therefore, even if the user is not using the 802.11 interface for a while, the software does not shut the AP down because of inactivity but it waits a time period to confirm the inertia or change its evaluation. The time period it waits can be statically adjusted.

If, after the inactivity margin there are no connections and no one is advertising its presence under the coverage, then the AP will shut down its Wi-Fi module. One can notice that this approach works properly in presence of one or more users under the coverage.

V. RESULTS

The Fig. 4 below shows our measurement setup.

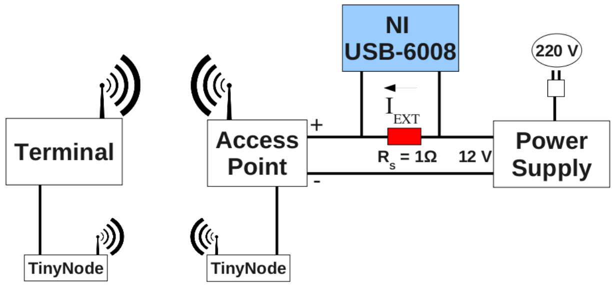

Figure 4. Measurement setup

The terminal is connected to a low-power radio module, which sends "reverse beacons" to another low-power radio module connected to the Wi-Fi AP. The electric DC current consumed by the AP from its power adaptor is measured with the traditional method of a voltage drop over a shunt resistor. The value of the resistor (1 Ohm) is selected in a way that the voltage drop is negligible compared to the supply voltage (12V), so that the error introduced is minimized. The voltage on the resistor is measured by the acquisition device NI USB-6008. The measurement data is processed and logged by LabView on a PC (not shown) connected to the USB-6008.

The low-power radio module at the AP operates in Rx mode only. In this mode, the power consumption of the TinyNode is around 10mW, which is negligible compared to the total consumption of the AP (2-3W). Therefore, in our experiments we could safely ignore the overhead in the power consumption introduced by the low-power radio module.

A. *Static experiments*

In the first experiment we evaluate the average consumption P of the AP in the two cases: Wi-Fi radio on and Wi-Fi radio off. Here we measure the electric current with a multimeter attached between the external power adapter and the AP.

Table II summarizes the static results we have obtained.

TABLE II. LINKSYS WRT54G V3.1 – ELECTRICAL PARAMETERS

	Wi-Fi interface ON	Wi-Fi interface OFF
P [W]	3.36	2.48

Based on the results in Table II we can now present on Fig. 5 the share of the Wi-Fi interface related to the whole (internal) Linksys WRT54G AP power consumption.

The maximum hypothetical power saving that we can achieve would occur if the Wi-Fi interface is always switched off. So, the maximum hypothetical power saving will be the power consumption share of the Wi-Fi interface, that is: 26.19 %.

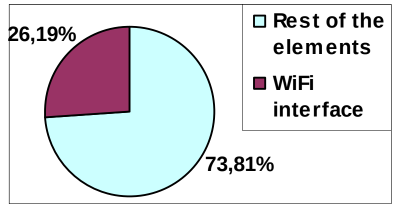

Figure 5. Share representation of the power consumption in the Linksys WRT54G Wi-Fi Access Point

B. *Dynamic experiments*

With the setup from Fig. 4 we ran experiments to obtain traces of P_{EXT} over time.

The aim of this experiment is to emulate the behavior of the proposed solution over an entire day, we decided to run one hour long simulation to keep trace of the current consumption trend over time.

Within one hour we have half an hour of heavy activity (Wi-Fi interface on) and the rest of complete inactivity (Wi-Fi interface off). For both cases we evaluate the maximum and minimum value in terms of power consumption: we use a moving average with a relatively small window (1 second) in order to protect the max evaluation against isolated peaks.

On Fig. 6 an important part of the power trace is shown. In particular, it emphasizes the power step and the response delay whenever a user needs to wake up the AP.

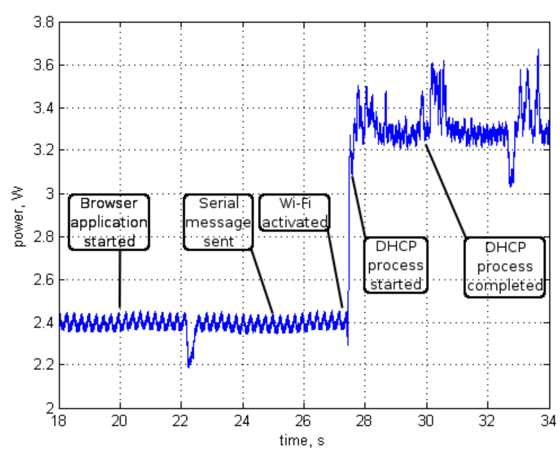

Figure 6. Total power consumption (P) over time

Afterwards, given the power consumption in on/off mode we build the daily model by expanding the previous simulation over 24 hours.

Based on the activity pattern of the user, we can estimate what will be the real power saving (Δ) with our approach. If we assume that over a period of time t the user needs an Internet connection for time t_1, we can introduce the usage factor $\lambda = t_1/t$. With t_1 and t large enough, it can be shown that Δ =

$\Delta_{max}(1- \lambda)$, where Δ_{max} is the maximum hypothetical power saving.

To get meaningful results we used the average daily usage values provided by iPass Inc., which aggregates Wi-Fi hotspot networks for businesses purposes. Following the latest iPass index [12] we get for a daily session an average length of 91 minutes of Wi-Fi usage (worldwide).

Table III summarizes our results.

TABLE III. SIMULATION MODEL RESULTS

Usage factor (91 min per day)	6.3 %
Power consumption Wi-Fi ON *	3.604 [W]
Power consumption Wi-Fi OFF *	2.637 [W]
Power saving factor	25.14 %

* Average evaluation over 900 seconds

Another aspect we will treat is the delay analysis of the wake up process.

We define the complete wake-up from a user point of view: starting from the launch of the application, that triggers the AP wake-up procedure, until the Internet connection is activated and the application is able to work on it. From our simulation results we established that, on average, a complete wake-up delay is around 10 seconds. In Table IV, we specify the different processes which contribute to the wake-up delay.

TABLE IV. WAKE-UP DELAY ANALYSIS

	Relative Time [m:ss]
Browser application started	0:00
Serial message Terminal/TinyNode sent	0:05
AP's Wi-Fi interface activated	0:07
DHCP process started	0:07
DHCP process completed	0:10

The main contribution to this delay is introduced by the Debian kernel to realize that it can not send any packet on the Wi-Fi interface. It has to try to deliver some packets before producing an interrupt to signal the problem.

A significant delay is also introduced by DHCP process. In further improvements the average value can be lowered down introducing out-of-band piggybacking or a different management for the IP addresses.

VI. CONCLUSIONS

Introducing a sleep mode into home femto base stations, to fulfill eco-sustainability requirements, ensuring in the meanwhile a short wake-up delay, is a critical issue. In this paper, we have introduced a "reverse paging" concept, using ultra-low consumption properties of radios made for sensor network modules.

We have set-up a prototype with a popular Wi-Fi Access Point and measured the electrical consumption gain and wake-up delay. The solution provides significant energy saving even with our particular prototype, where the AP has not been designed with energy-awareness in mind and the AP's non-Wi-Fi components have a huge share of the overall power consumption. As shown in the previous Section, if the consumption of the non-Wi-Fi components of the AP is minimized (easy to achieve in new designs with modern components) the reduction in energy consumption of APs will be huge.

We analyzed that the two main causes of the wake-up delay are kernel signaling and DHCP exchange at each AP wake up. Both delay sources can be worked on, and subsequently, the total wake-up delay can be significantly reduced.

Other important advantage of this solution is the health argument, as there are no more unnecessary radiations when the equipment is not used actively. The security aspect is also a plus, as the AP is switched off when its usual user is away.

This solution has market perspective as we used standard 802.11 radio modules, with no need for standardization effort. The system components are simple and cheap. Access Point, femtocell or Set Top Box manufacturers could easily insert this eco-designed functionality in their future products.

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