# Energy-Conscious Prototype for Enabling Multi-Protocol Wireless Communications


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***Abstract*—In this paper, we present a novel hardware prototype implementation of a wireless communication system capable of automatically selecting one of several available commercial standards in order to minimize energy utilization while simultaneously achieving reasonable data rate performance. Without loss in generality, two wireless standards were employed in the prototype implementation, namely: ZigBee and WiFi. These standards were chosen due to their complementary characteristics with respect to data bandwidth and energy efficiency. At the core of the prototype implementation is a *decision-making module* designed to automatically select the most suitable wireless standard for data transmission based on the instantaneous network load and the operating conditions of the wireless platform, such as battery life. The prototype implementation was evaluated across several data transmission scenarios, including file transfers, web browsing, streaming media and text messaging. By leveraging the concepts of sensing and adaptation often employed in *cognitive radio*, the prototype system monitors and selects the lowest power intensive wireless protocol while still maintaining an acceptable quality of service for the desired application. Even though performance transparency could not be sacrificed for power efficiency, experimental validation of this network design shows substantial energy savings: more than a 30% reduction in energy consumption of the wireless interfaces is possible, leading to a substantial increase in the effective battery lifetime of a energy-limited wireless networking device.**


## I. Introduction

Modern society's usage of wireless communication devices is growing at an exponentially increasing rate, driven primarily by the cellular telephony and mobile computing markets [1]. However, this growth comes at the expense of global energy consumption used to enable these devices and the infrastructure used to support them. According to [2], it was stated that "currently 3% of the world-wide energy is consumed by the ICT (Information & Communications Technology) infrastructure that causes about 2% of the world-wide CO2 emissions, which is comparable to the world-wide CO2 emissions by airplanes or one quarter of the world-wide CO2 emissions by cars." Consequently, given this level of energy consumption and its associated impact on the environment, coupled with minimal advances in the battery technology sector [3], has made energy efficiency and power saving strategies an increasingly important design requirement for modern wireless devices.

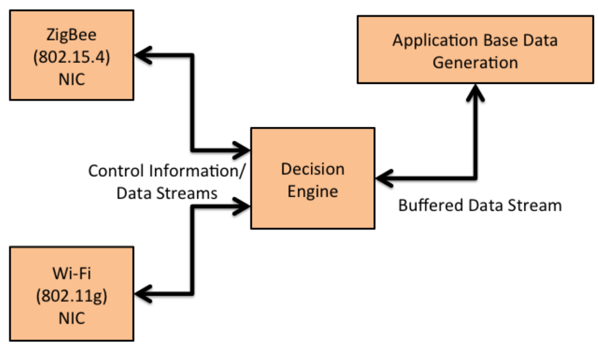


Fig. 1. System concept diagram of the proposed energy-conscious prototype implementation, showing how network traffic is filtered by a decision-making engine in order to decide which networking interface should be employed at both the transmitter and receiver modules. The two networking interfaces shown here are ZigBee (IEEE 802.15.4) and Wi-Fi (IEEE 802.11g).

With the rapidly growing adoption of smart phones, laptops, netbooks, and portable tablet computers by modern society, the ability for a wireless mobile device to save power in order to extend its battery life has been a very active area of research and development by both industry and academia. In terms of reducing wireless communications power consumption, one approach that can be employed is to utilize multiple wireless protocols in order to achieve some degree of power savings while still maintaining an acceptable level of data bandwidth for performing mobile tasks. Many mobile devices support several wireless protocols, such as Wi-Fi, Bluetooth, and 3G. In [4], the benefits of such a combined protocol network was investigated. Specifically, two networking standards were employed by a single wireless system, namely, Bluetooth and Wi-Fi. The actual prototype used complex switching intelligence and the advantages of using a multiprotocol network and important switching characteristics were examined. Furthermore, several switching policies were studied in order to assess whether power saving methods can be realized via the reduction of Wi-Fi activity. The policies used several measurement techniques, such as received signal strength indicator (RSSI) metrics, transmit power, link quality, and bandwidth capacity. These measurements were obtained in order to determine the appropriate switching times between wireless protocols [4]. Bandwidth was the primary metric for the switching calculations performed in [4]. Although several of the techniques proved to be unsuccessful, power savings were realized but at the price of mobility. The primary issue with this design was the use of Bluetooth technology.

In practice, Bluetooth is not a suitable choice for mobile applications due to its limited transmission range. Rather, Bluetooth was developed as a cable replacement protocol and not for multiuser mobility. For this reason, Bluetooth has a very short transmission range making it much less effective relative to other low-power wireless access technologies [5]. With an infrastructure based network, Bluetooth provides insufficient mobility and thus seriously limits users or vastly increases the need for additional access points. In this paper, we implement a hardware prototype system designed to minimize power consumption and achieve a reasonable level of data bandwidth on demand by automatically switching between the power efficient, low data rate wireless data transmission standard called ZigBee and the high power, high data rate wireless data transmission standard referred to as Wi-Fi. These protocols will be controlled through an onboard algorithm that monitors the bandwidth of a wireless network, reacting to increases and decreases in network activity, deciding when to switch between protocols. The algorithm monitors the bandwidth of the active wireless systems, and correlates predetermined power consumption to that usage, which was obtained via pre-profiling the communication interfaces. Thus, when the wireless network requires more capacity, the algorithm selects the Wi-Fi interface for data transmission/reception, and when little to no data capacity is needed the algorithm selects the ZigBee interface. Intuitively, this dual protocol switching approach possesses a power advantage due to the generally limited amount of network activity of mobile devices compared with the duration of their uptime. This design overcomes the shortcomings of current single protocol networks by:

1) Alternating between two complementary wireless standards without sacrificing mobility and throughput, and decreasing communications power consumption over time.
2) Intelligently monitoring the bandwidth of multiple radios directly and reactsing to changes in the bandwidth.
3) Being power consumption aware by making decisions as well as alternating automatically based on power consumption, bandwidth needs, battery level, etc.

The rest of this paper is organized as follows: In Section II, we present the overall proposed communication system, while in Section III we describe the power profiling process of the communication interfaces as well as the implemented hardware prototype system. In Section IV, the actual experiments with the hardware prototype and the experimental results are presented, and several concluding remarks are drawn in Section V.

TABLE I
A COMPARISON OF WIRELESS STANDARDS EMPLOYED IN MOST MODERN MOBILE WIRELESS DEVICES [4], [6]–[10].

| Qualifier | Wi-Fi | ZigBee |
|---|---|---|
| Data Rate | 54 Mb/s | 250Kb/s |
| Transmission Power Draw | 32-100mW | 0.001-.003mW |
| Idle Power Draw | 0.085W | 0.001-.003mW |

## II. PROPOSED COMMUNICATION SYSTEM

The concept diagram for the proposed prototype system is shown in Fig. I. The prototype implementation uses a hybrid Wi-Fi and ZigBee interface in order to provide improved power efficiency for mobile devices while not sacrificing data bandwidth requirements. Thus, from a network perspective, each node in the network can be equipped with both a ZigBee and a Wi-Fi radio interface such that the appropriate interface can be selected by a decision-making algorithm running onboard the system. Based on the idle power consumption of typical Wi-Fi and ZigBee radios (see Table I), this concept has the potential to realize a large reduction in power consumption for an idle system. However, the actual power savings heavily depends on the switching characteristics. The proposed implementation uses commercially available networking interfaces and thus does not require any significant hardware changes. A ZigBee interface, which already exists in many commercial mobile devices, was installed. ZigBee is a low-power and low-cost interface, making it relatively inexpensive to install on many current mobile devices, such as cellular telephones.

## III. PROTOTYPE IMPLEMENTATION

### A. System Architecture

The experimental prototype is designed to evaluate the performance of the proposed communication system as well as single protocol communication devices across a range of network applications. The network topology was designed to infrastructure-based, which is a mode of operation that is generally employed more often by Internet-ready wireless devices. Without loss in generality, the prototype implementation will only utilize two nodes, a mobile user and a base station or router. All power savings and adaptive protocol switching will focus on the mobile user. Since it is assumed that the base station will operate using a stable power source, its energy consumption will be neglected in this research.

Data for the network is generated in order to represent typical Internet usage for a given duration. This data is then buffered into a single queue, as seen from Fig. I, then the switching engine determines which interface will transmit this

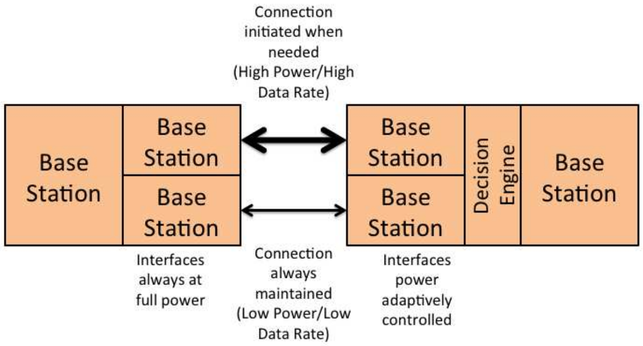


Fig. 2. A system diagram of the prototype implementation setup with both external networking interfaces being monitored in real-time. Both wireless networking interfaces are monitored directly to provide direct information about power consumption, and allow for evaluation of the switching intelligence of the mobile user.

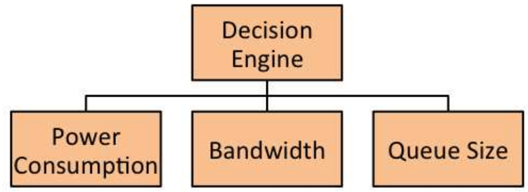


Fig. 3. Breakdown of operating parameters for the decision engine employed in the prototype implementation.

data. At all times, the ZigBee connection will be maintained and Wi-Fi will be initiated through the transmission of ZigBee control packets when additional bandwidth is demanded. Since bandwidth can be relatively difficult to measure from two independent interfaces quickly, the data queue is used instead to measure the bandwidth. Based data queue characteristics, relative data rates can be determined.

The tests performed by the mobile user represent common applications performed by mobile devices such as smart phones. The four applications examined in this work were: large file transfers, small file transfers, web browsing, and purely idle utilization. All relevant data was captured by a third data acquisition computer workstation. From this workstation, the data is viewed graphically in real-time and exported to a file for analysis.

The ZigBee interface was the most challenging to construct due to the limited sophistication of the selected modules. A relatively simple version of TCP was built upon the open-source API xbee-api [11]. The implementation provided the necessary functionality in order to maintain links between the ZigBee modules and the complete bi-directional file transfers. This was abstracted in the devised switching engine in order to simplify the interface.

The switching engine itself dynamically alternates between the ZigBee and Wi-Fi interfaces by using three primary parameters: bandwidth, queue size, and power consumption. Power consumption was predetermined directly via measurements, and was directly related to the transmission usage. Therefore, at any given time, the power consumption could be determined via data bandwidth usage. This switching engine not only possessed the ability to direct data flow, but also to initiate connections of the interfaces and reduce their overall power as well. This switching engine was only developed on the mobile user, the base station or routing unit would remained at full power on both interfaces at all times.

The base station device effectively acts as a wireless hub which supports both ZigBee and Wi-Fi capabilities, keeping both interfaces active at all times. The mobile node was responsible for running all network utilization tests and has both wireless interfaces power consumption actively monitored. A third data acquisition machine was originally used for power profiling, and then to measure power usage during experiments. It utilized a pair of multimeters in order to capture detailed power usage of the mobile user. From this data, energy was determined of the networking interfaces during transmit, receive, and idle modes. These results can be seen in Table III.

### *B. Hardware Components*

The base station and mobile node are virtually identical hardware components built around the Eee PC 4G Netbook, as shown in Fig. III-B. Each netbook runs a standard version of the Ubuntu 9.10 operating system. The mobile node uses a Linksys WUSB54G wireless interface adapter for Wi-Fi, and a XBee Series 2 OEM RF Module for ZigBee. The Wi-Fi module uses hand compiled drivers based upon the MadWifi driver. Unless otherwise noted, all Wi-Fi traffic was performed in constantly active mode (CAM), due to that fact that only an ad-hoc wireless can could be utilized for direct connections between netbooks. Also Wi-Fi connection information is passed through the always on ZigBee connection to primarily reduce the association time of Wi-Fi.

### *C. Protocol Alternating*

The basic switching process encompasses a start-up process for the higher-level radio that incurs some delay. The initial switching process can roughly be divided into three parts: connection initiation request, power-up, and connected. Since the ZigBee channel is always available for communication, data transfer continues until the switch to use the Wi-Fi interface is complete. Both interfaces are abstracted as a single interface to the operating system. Data is first buffered into a queue

TABLE III
WI-FI AND ZIGBEE POWER CONSUMPTION MEASUREMENTS.

| Protocol | Action | Power(W) | STD(W) |
|---|---|---|---|
| ZigBee | Tx (Average) | 0.365 | 0.001 |
| ZigBee | Rx (Average) | 0.360 | 0.003 |
| Wi-Fi | Tx (Average) | 1.454 | 0.005 |
| Wi-Fi | Rx (Average) | 1.402 | 0.006 |

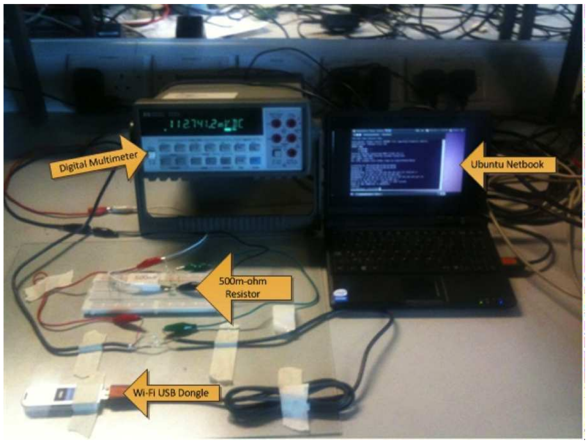


Fig. 4. Photograph of the actual hardware prototype implementation with only a single multimeter, which is being employed in order to measure the power consumption of the Wi-Fi USB dongle.

that leads to both interfaces. Then based upon the amount of data in the queue and how quickly data is added or removed from it determines when to switch between the interfaces occurs. This switch causes a switch in the queue's output interface as well, forcing data either through only ZigBee or only Wi-Fi. These thresholds are based upon measured power characteristics of the physical wireless hardware, the battery level of the node, and application demand. Since a design requirement was performance transparency, most tasks need to use Wi-Fi to transfer data without considerable delay visible to the user. Therefore application demand does trump most switching decisions. Wi-Fi association time was highly focused upon to reduce possible lag during switches.

## IV. Experimental Setup

### A. Experimental Results

Fig. IV-A shows an overview of the benefits provided by the proposed implementation, compared to a Wi-Fi CAM, Wi-Fi PSM, and ZigBee showing both energy and time for a variety of transfer task-base tests. These results represent power consumption per activity. It is important to note that for most mobile devices that greater that 70% of device uptime is spent is idle mode. Although dynamic switching the mobile device can remain out of the power hungry Wi-Fi idle state, and only utilize it when larger data load become queued. On its own, the ZigBee interface provides the lowest energy consumption advantage during idle testing, but as soon as any bandwidth intensive task is performed it becomes very power inefficient. Wi-Fi is very power efficient when it comes to data transfer, but when the node becomes idles this is no longer the case. The proposed network implementation shines in both these cases, expect when the Wi-Fi interface must be maintain for more than 70% of the device's uptime. Fortunately for mobile users, 70% network utilization time is extremely rare. Overall, when compared with Wi-Fi, the less time the node is actively transferring data the more energy is saved with the proposed network implementation. The graph

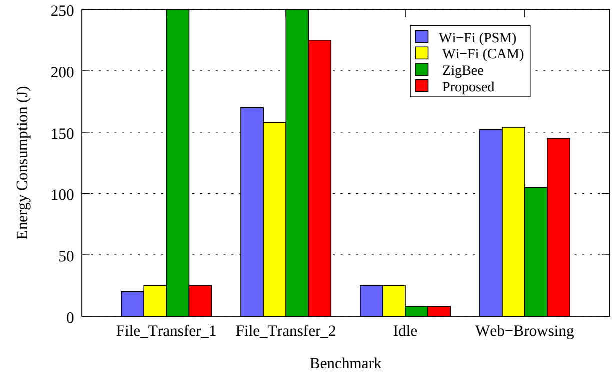


Fig. 5. Experimental results from the four tests used to evaluate the performance of ZigBee (Green), Wi-Fi PSM (Red), Wi-Fi CAM (Blue), and the proposed implementation (Purple). File transfer 1 (Far left test) examines the power usage of a transfer that last for 25% of the test duration. File Transfer 2 (Second from left) transfers a file for 80% of the test. The Wikipedia or web-browsing test (second from right) examines common web-browsing usage across a 60 second interval derived from the IMIX web studies of web-browsing habits. [12] The final test (far right) examines power usages for 20 seconds during active no transfers or an idle state.

below illustrates this fact, extrapolated from measured result of the implemented hardware.

Fig. IV-A are the results of a 56% high demand transfer test. The figure illustrates the power savings over time. Even at such a high data transfer rate a 10% decrease in overall power consumption is observed, which as previously explain is an extremely rare usage percentile. Extrapolating from this data, a saving of 53% can be saved.

### B. Power Measurement Strategy

The energy measurement setup consists of a HP DAQ Multi-meter data acquisition device connected to a standard Windows XP desktop system with MATLAB. The individual power rails for Wi-Fi and ZigBee are monitored by placing separate 1%-tolerance 500 m$\Omega$ resistors in series with each subsystem's power supply. Samples are measured at 500 ms intervals, the maximum speed of the multi-meters. Energy,

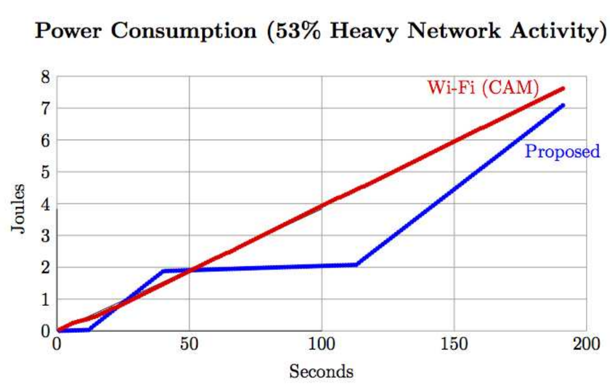


Fig. 6. The above graph compared the amount of energy used over a two minute file transfer test with 53% activity between a single protocol Wi-Fi (CAM) network and the proposed network.

and not power consumption, is used to show the majority of the results because it captures both the power and time aspects of a particular benchmark. Other components, such as processor, power regulators, memory, and display are not included since despite the fact that they are significant power consumers of the mobile device's battery, they cannot be easily directly measured independently.

Since power consumption monitors do not exists on common network interface cards, it was assumed that direct real-time measurement and feedback would be impractical. Therefore a power profile was determined for each network interface cards. With this profile data, at any data-rate the power being consumed could be calculated in real-time indirectly. This data was then directly used by our decision engine to make determinations when to alternate protocols. This profile was compared with direct measurements during testing to confirm proper switching and assumed power consumption.

## V. Conclusion

With an ever-increasing focus of today's world today on mobile data connectivity, greater efficiency when performing data communications while using these mobile devices is growing in importance. The work presented in this paper is a step in a positive direction with respect to energy efficient wireless devices. Using off-the-shelf components highlighted the fact that energy efficient approaches can be readily realized using today's technology. Combining the ubiquity of wireless devices and the ever growing marketplace, multiprotocol systems show tremendous promise for the future. The applications for multiprotocol systems are far ranging, from large scale communication networks, to household appliances and networks. The greatest advantage is the simplicity of the proposed concept. The prototype implementation achieved the following goals:

1) A Multi-protocol Networking Device: The system was able to utilize dual radio protocols to transmit data synchronously.
2) Power Efficiency: The system was able to considerably reduce the communications power consumed compared with a single protocol network.
3) Performance Transparency: The multiprotocol network performed equally or greater than the a single protocol network as in terms of throughput.
4) Commercially Available Equipment: This project only utilized off the shelf part in both nodes of the network.

By demonstrating the feasibility of this prototype implementation via practical means, this work has provided a foundation for future research and development efforts in the area of multiprotocol systems designed to satisfy both power efficiency and bandwidth requirements.

## References


[1] I. Mansfield. (2009) Worldwide mobile phone sales down by 5% in Q4 '08. [Online]. Available: http://www.cellular-news.com/story/36315.php?s=h

[2] e-Mobility European Technology Platform. (2008) 1st international workshop on green wireless 2008 (W-GREEN). [Online]. Available: http://www.cwc.oulu.fi/workshops/W-Green2008.pdf

[3] D. Lagesse. (2009) US News: Money. [Online]. Available: http://money.usnews.com/money/blogs/daves-download/2009/04/09/batteries-cant-keep-up-with-smartphones

[4] T. Pering, Y. Agarwal, R. Gupta, and R. Want, "Coolspots: Reducing the power consumption of wireless mobile devices with multiple radio interfaces," in *Proceedings of the 4th International Conference on Mobile Systems, Applications and Services*, Uppsala, Sweden, Jun. 2006.

[5] N. Baker, "ZigBee and bluetooth strengths and weaknesses for industrial applications," *Computing Control Engineering Journal*, vol. 16, no. 2, pp. 20 – 25, 2005.

[6] G. Anastasi, M. Conti, E. Gregori, and A. Passarella, "802.11 power-saving mode for mobile computing in Wi-Fi hotspots: Limitations, enhancements, and open issues," *Wireless Networks*, vol. 14, no. 6, Dec. 2008.

[7] E. Ferro and F. Potorti, "Bluetooth and Wi-Fi wireless protocols: a survey and a comparison," *IEEE Wireless Communications*, vol. 12, no. 1, pp. 12–16, Feb. 2005.

[8] C. E. Jones, K. M. Sivalingam, P. Agrawal, and J. C. Chen, "A survey of energy efficient network protocols for wireless networks," *Wireless Networks*, vol. 7, no. 4, Aug. 2001.

[9] J. Gutierrez, M. Naeve, E. Callaway, M. Bourgeois, V. Milter, and B. Heile, "IEEE 802.15.4: A developing standard for low-power low-cost wireless personal area networks," *IEEE Network*, vol. 15, pp. 12–19, 2001.

[10] J.-S. Lee, Y.-W. Su, and C.-C. Shen, "A comparative study of wireless protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *Proceedings of the 33rd Annual Conference of the IEEE Industrial Electronics Society*, Taipei, Taiwan, Nov. 2007, pp. 46 –51.

[11] A. Rapp. (2010) xbee-api: A java API for digi XBee/XBee-Pro OEM RF modules. [Online]. Available: http://code.google.com/p/xbee-api/

[12] R. Levering and M. Cutler, "The portrait of a common HTML web page," in *Proceedings of the 2006 ACM Symposium on Document Engineering*, Amsterdam, The Netherlands, Oct. 2006.