Understanding the Role of Transmission Power in Component-Based Architectures for Adaptive WSN

Guillermo Rodriguez-Navas
Malardalen Real-Time Center (MRTC)
Mälardalen University, Sweden
E-mail; guillermo.rodriguez-navas@mdh.se

Miquel A. Ribot and Bartomeu Alorda
Departament de Física
Universitat de les Illes Balears, Spain
Email: bartomeu.alorda@uib.es

***Abstract*—Component-based architectures can play an important role in solving some of the problems related to energy management in Wireless Sensor Networks. It has been recently shown that real-time interfaces, and their associated mechanisms for online adaptation, are useful for solving the problem of dynamically allocating bandwidth in a WSN, while still satisfying both quality and energy constraints. In this paper we will discuss the relevance of extending this model with a new parameter, the transmission power of the nodes. Based on experimental data, it will be shown that this parameter has a strong impact on both the energy consumed by the nodes and the quality/reliability of the communication. The integration of this feature with the notion real-time interface, although not completely solved, will be discussed as well.**

***Keywords*-WSN; power-aware systems; wireless sensor networks; component-based architecture; real-time interfaces**

I. INTRODUCTION

Wireless Sensor Networks [1] are a paradigmatic case of resource-constrained systems. When compared to other networks, WSN present two specific constraints: the limited energy available for the nodes and the dynamic and somehow unpredictable environments in which they are usually deployed. These challenging issues have turned WSN into a field of research in itself, with novel problems that are being addressed from many different perspectives.

Among these new challenges, the need of developing mechanisms for reducing the energy locally consumed by a node has received substantial attention, e.g. see [2]. But equally important is to be able to understand how the energy is used from a global perspective (application-wise) and thus allow the system to make energy-related decisions that are globally meaningful. In a recent work, it was shown that component-based architectures can play an important role in solving such kind of problems [3]. That work presented a mechanism that reduces the global energy consumption of a WSN by means of mechanisms that allocate resources (in their case, bandwidth) dynamically, either locally or globally, depending on the current state and requirements of the system. Such mechanisms were based on a hierarchical component-based architecture with real-time interfaces [4].

Such mechanisms assume that there is an indicator, called the *global quality index*, that quantifies how good the system is behaving with respect to some application objective. Moreover, they assume that each component has a number of possible *operation modes* and that for each operation mode there exists a clear (and quantifiable) relationship between, on the one hand, the provided quality and, on the other hand, the bandwidth and energy consumed. Under these assumptions, they show that it is possible to solve two problems: (1) The *offline* optimization problem of determining the global configuration (i.e. the operation mode specifically assigned to each node) that gives the best global quality without exceeding some given bandwidth and energy constraints. (2) The *online* optimization problem of adapting to runtime changes of the system. Such changes may be due to two types of events: (a) external events that change the importance of one or more nodes, and (b) significant changes of the available energy of some nodes. Due to the complexity of this problem, the algorithms proposed rely on heuristics for finding suboptimal solutions in a reasonable time.

The aim of this paper is not to refute this approach, but to highlight the need of extending it in order to include the notion of *transmission power*, because of its close relationship with both quality and energy consumption. However, it is important not to confuse the novel problem presented in this paper with the problem of scheduling the active/sleep states of the nodes of a WSN, which is often called *power scheduling* [5], [6]. Our work purports to go one step further and study the impact of varying the transmission power *during* the active state.

Nevertheless, including this concept in the existing formalisms for real-time component-based systems, such as the real-time interfaces, is not straightforwardl. Transmission power is a notion that made no sense in the context of the traditional processor/network scheduling techniques and consequently it has never been part of the theory of real-time systems. For this reason, we claim that, first of all, it is important to understand the role played by power transmission in WSN and how it relates to the dynamic allocation problems discussed in papers such as [3]. This paper will discuss the experiments we have conducted in order to study these properties and will give some ideas about how the obtained results can be integrated in the

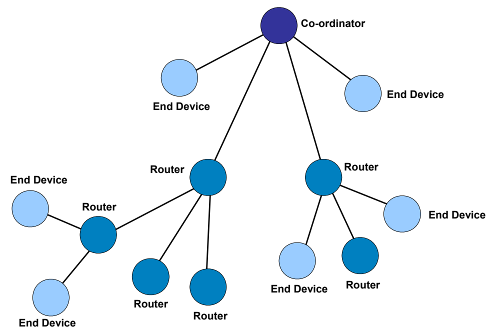


Figure 1. Example of a cluster-tree hierarchical topology

framework of component-based architectures with real-time interfaces.

II. Problem statement

A. Considered applications and topology

In this work we consider applications that require deployment of a large number of sensor nodes for carrying out some kind of inspection/monitoring task over a wide geographical area. It is also assumed that this application must dynamically react to changes of the phenomena monitored, for instance in order to follow interesting events happening in a specific subarea. As indicated in [3], the WSN topology known as *cluster-tree* is very suitable for such applications.

In this topology, there exist two types of nodes, the end devices (ED) and the control coordinators (CC), which collaborate as follows. The end devices are the sensing nodes, so each one of them gathers information and sends it (in the form of packets) to a final destination, usually called the *sink*. For simplicity and also reducing the global bandwidth requirements, EDs that are close geographically actually send their data to the same intermediate node, therefore forming a communication cluster. The node coordinating this cluster (the CC) has the function of gathering the data streams of said EDs into a data stream that is directed to a higher level of the tree architecture. Coordinators can also be grouped in clusters, forming thus a hierarchical structure, as shown in Figure 1. In such cases, the intermediate coordinators are called *routers* and the upmost coordinator is called PAN coordinator or just Coordinator.

B. Related work

It is widely accepted that in order to reduce the energy consumption of a WSN, it is fundamental to switch off (or put to sleep) the nodes that are idling [5], [2], [6]. This is due to the fact that the energy required by the processor and the communication hardware of a node is relatively high even if the node is just waiting for reception and not sending data. This circumstance raised a very interesting research problem: what is the best way to schedule the changes of state of the nodes, from active to sleep and vice versa, in order to significantly reduce the energy consumption? This problem is usually called *power scheduling* and has received a lot of attention in the last years.

Most of the solutions addressing power scheduling are based on variations of the Time-Division Multiple Access (TDMA) technique. This allows senders and receivers to wake up only during their preassigned time slots, what notably reduces the consumed energy. As usual in TDMA schemes, the most difficult issues are guaranteeing temporal consistency among the distributed TDMA patterns and introducing flexibility [5], [6]. However, for the purpose of this paper, there is only aspect of power scheduling that is relevant: the fact that the state of a node is treated as a boolean variable. A node may be either active (1) or sleeping (0); meaning in high-power or in low-power state. But this is a rather simplistic description of the possible energy states of a WSN node.

For this reason, more recent research has enriched this limited definition of state with the notion of *operation mode*, which constitutes a sort of sub-state of the active state. The notion of operation mode was firstly introduced in the field of processor scheduling, for instance in the form of frequency hopping or voltage scaling schemes[7], and has proven to be particularly well suited for scheduling soft real-time systems. Operation modes imply that it is possible to make a tradeoff between the quality of a certain task and the amount of time and energy its computation needs. In general, any task will require more energy for improving its quality, either in the form of higher clock frequency or in the form of longer computation time. When this model is applied to communication networks, like in [3], improving the quality of a task also increases the bandwidth it requires, since more computation implies more data transmitted.

The problem of scheduling tasks with operation modes has recently been addressed with the help of components and real-time interfaces (RTI), because RTI reflect the concept of demand and service in a very flexible way [4]. RTI allow three types of components: load components, service components and process components. A *Load component* typically represent one stream of events to be processed and it is usually characterized by a load curve $\alpha(t)$ and a deadline d. A *Service component* represents the resource available and it is characterized by a service curve $\beta(t)$. A *Process component* connects the load and the service, because it is in this component where the service is consumed for processing the events.

Figure 2 depicts how the three components are composed and what information they exchange in their interfaces, namely the input assumptions (α^A, β^A) and the output guarantees (α^G, β^G). The key idea of the RTI is to provide enough information during composition so as to decide whether two or more components can work together properly. The relationship can be read like this: as long as a certain (assumed) load is not exceeded, the process

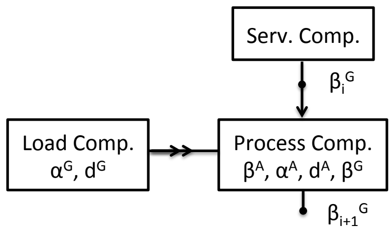


Figure 2. Component composition with real-time interfaces (simplif.)

guarantees that the consumed service will be at most a certain (guaranteed) amount.

More specifically, the notion of operation mode is used in [3] like a modifier of the process component. Note that, since the operation mode indicates how much load can be processed and how much service is required for it, changing the operation mode of a node (it is, its quality) is equivalent to replacing the corresponding process component with a different one. If this new process component is composable with the rest of the components then the system is schedulable and thus the change can be performed. But, because in WSN the energy consumed by the chosen operation mode also constitutes a constraint, the energy required by the new component is also checked for deciding whether the replacement is possible or not. The reciprocal is also true: a change of the load or a change of the energy of one node could force a change of its operation mode and thus of the corresponding process component, what would change the composition of the whole system.

C. Open questions

So far, the concept of operation mode has embraced only the possibility of changing the parameters of the computation. An aspect that has not been considered yet, although it is a feature included by many modern WSN nodes, is the possibility of changing the power used for transmitting information. In order to include this new dimension into the problem of scheduling power-aware systems, it is important to answer first the following questions:

1) How does the used transmission power affect the energy required for processing/transmitting an event?
2) How does the used transmission power affect the quality of the processing/transmission of said event?
3) How can we compose this parameter with the other relevant parameters of the system? Can RTI be applied (as they are usually defined) to this problem?

The first two questions can be answered experimentally.

III. Experimental platform

This section summarizes the main characteristics of the nodes that have been used for obtaining experimental data, and discusses the new definition of operation mode they use.

A. Physical properties of the IEEE 802.15.4 standard

The IEEE 802.15.4 standard defines the physical layer and the Medium Access Control for low-rate wireless personal area networks (WPAN)[1]. Several higher layer protocols, most notably ZigBee, are developed upon the IEEE 802.15.4 stack. IEEE 802.15.4 has a typical communication range of 5 to 75 meters and was designed for operating in one of three unlicensed frequency bands of ISM: 2.4 GHz, 915 MHz and 868 MHz. However, without losing generality, in the rest of the paper we will consider only the 2.4 GHz frequency band because it is the only one available worldwide and, moreover, provides the highest transmission rate among the three. The standard also specifies that each receiver must have a sensitivity of at least -85 dBm and a transmission power in the range from -25 dBm to 0 dBm.

B. Characteristics of the nodes

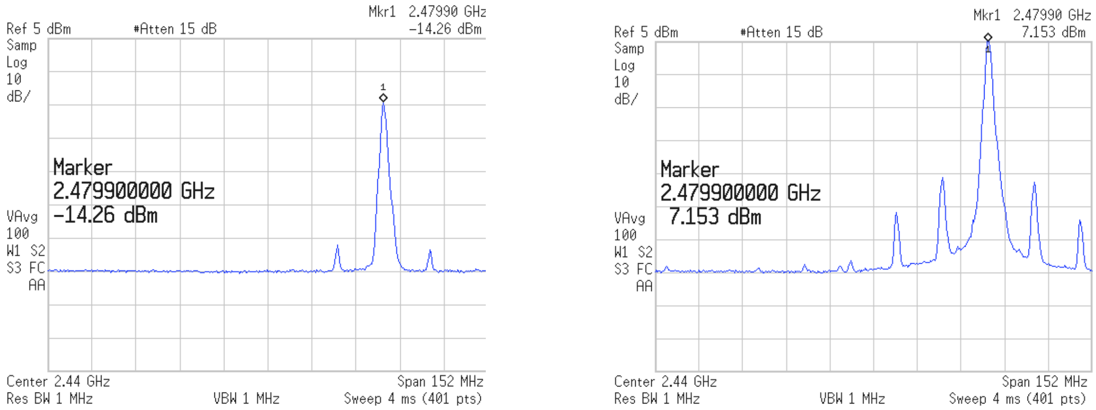
For obtaining experimental data, we have used the ZigBee Evaluation Kif of Jennic. This kit provides the hardware and software needed for developing a network of sensor nodes [8]. It includes one DR-1047 Controller Board along with four DR-1048 Sensor boards. Each board incorporates a number of sensors as well as a microcontroller JN5139, all integrated in a compact module. This kit also includes two modules amplifiers that enable higher-power transmission.

An important feature of the JN5139 microcontroller is that it incorporates an integrated radio transceiver. This transceiver includes the following elements: a radio module, a modem, a baseband processor and a security coprocessor. The receiver of the radio module has a sensitivity of 96 dBm, whereas the transmission power (P_{tx}) achieves a theoretical maximum of $+1$ dBm. Moreover, this module incorporates an adjustable RF power amplificator that supplies 6 different levels of P_{tx}. The nominal distance between two contiguous levels is approximately 6 dB, and the minimum level is -30 dBm. The baseband processor, which is intended to implement most of the features of the IEEE 802.15.4 standard, also sets which one of the six possible power transmission levels (PTL, for short) of the radio module is used.

For illustration purposes, Figure 3 shows two examples of measures of the transmission power generated by a node. They were captured with the help of a spectrum analyzer, and they show how the transmission power is distributed over frequency. Figure 3(a) corresponds to a node operating at PTL $= 1$, with High-power transmission enabled; whereas Figure 3(b) corresponds to a node operating at PTL $= 4$, also with High-power transmission enabled. Notice that there are small peaks at harmonic frequencies of the nominal channel frequency. These peaks constitute leaks of transmission energy and become more important as the PTL increases.

C. Specific operation modes

Energy is of paramount importance in any WSN network. Due to this, the processors used by WSN nodes



(a) PTL=1

(b) PTL=4

Figure 3. Example of two different P_{tx} levels; both cases with High-power transmission

typically provide very flexible operation modes, each one with different energy requirements. The difference between these operation modes is due to the number of devices that are active, so a node switches from one mode to another depending on its actual needs. For example, the ADC can be deactivated if the node does not need this functionality.

The notion of *power domain* refers to the set of devices that the node can activate/deactivate as a whole. The power domains available in the JN5139 microcontroller are: VDD domain, Digital Logic domain, Analog domain, RAM domain and Radio domain. Among them, the radio domain corresponds to the transmission and reception circuitry. It is controlled through the baseband processor.

Without going into too many details, the JN5139 microcontroller presents four main operation modes:

1) Active processing
2) CPU doze
3) Sleep
4) Deep sleep

The last two modes correspond to low-energy modes in which most of the domains are deactivated, including the CPU. In the CPU doze mode, the CPU is also deactivated, but the baseband processor is active and therefore Tx/Rx functions can be performed. In the Active processing mode the CPU is active (and consuming) whereas the other power domains can be activated or deactivated by software.

Note that, by bringing P_{tx} into consideration, the Active processing state can be now subdivided into 12 sub-states, what corresponds to two times the six available PTL, because for each PTL the high-power module can be On or Off. This notion, for instance combined with the idea of operation mode discussed in [3] would yield a total number of 36 states, each one with different energy consumption needs. The effect on the CPU doze state, although may have interest for certain systems, will not be considered in this paper, for the sake of simplicity.

IV. Experimental results

Once the specific operation modes of the nodes have been described, it is possible to study how these modes relate to some important attributes, such as energy consumption and communication quality.

A. Transmission power level vs. energy consumption

Our first set of experiments consisted in measuring the energy actually consumed by the different PTL during the Active processing state. Our goal was to determine the relative importance of this parameter, compared to the total energy consumption of the node. For this experiment, we developed a program that switched the operation modes gradually and we measured the input current of the microcontroller in each mode.

The results obtained for Low-power transmission are shown in Figure 4 and the results obtained for High-power transmission are shown in Figure 5. In both graphs, label A denotes Active mode with disabled communication, label B denotes Active mode with enabled communication but not transmission (it is, reception only), and the labels C–H denote Active and transmitting at one of the 6 different PTL, ranging from 0 to 5, respectively. The areas labeled with I and J correspond to sleep modes.

Both graphs show that the current consumed by the circuit increases significantly during the transmission phases, and that it actually depends on the transmission power used. In fact, the relationship between the current consumption and the PTL increases following an exponential law, which is much more pronounced for High-power transmission. Therefore, there is still room for improving energy management if the concept of PTL is properly handled.

B. Transmission power level vs. communication quality

Once it has been proved that the used PTL has a strong impact on the energy consumption, the next step is to measure how this parameter affects the quality of the application.

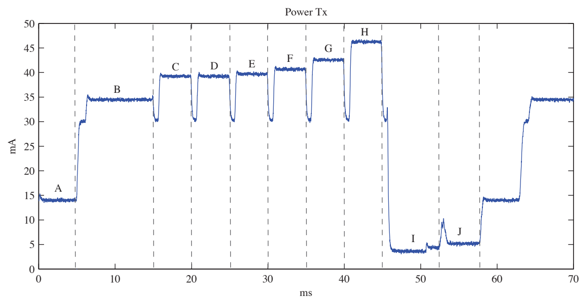


Figure 4. Current consumed (Low-power transmission)

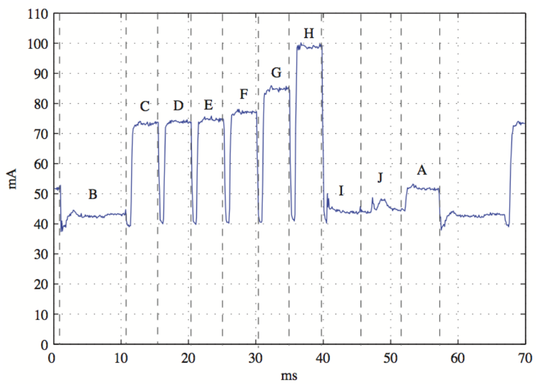


Figure 5. Current consumed (High-power transmission)

Since transmission power only concerns communication, the natural way to evaluate the quality achieved is through some kind of metrics for data communication. There are several indicators for evaluating the quality of a communication link. They can be divided in two groups: *instantaneous* indicators, which provide information about the quality of the physical signal received; and *statistical* indicators, which provide information about the number of packets received/discarded during a certain period. In our study, we will use one indicator of each kind: the Link Quality Indicator (LQI) and the Packet Reception Rate (PRR), respectively.

The LQI is a direct measure of the amplification gain required for correctly receiving a packet, and is measured in dBm. It is directly calculated by the communication hardware (in fact, by the modem) for each packet received according to some formulas discussed in the chip specification. The PRR is the ratio between the number of packets correctly received and the number of packets actually sent in a given period; it is also related to the concept of Packet Error Rate (PER) as follows: $\text{PRR} = 1 - \text{PER}$.

The PRR is usually considered the most objective indicator of the quality of a link [9], but it has the problem of requiring information from the transmitter (the number of packets transmitted) and from the receiver (the number of packets received) and therefore it cannot be determined by a single node in runtime. Due to this it is mainly used for

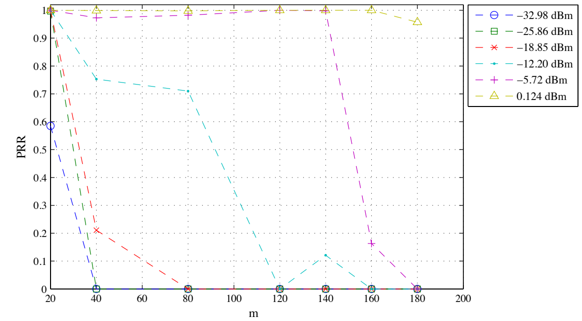


Figure 6. Observed PRR vs distance for the six PTL

evaluating the communication quality from the perspective of an external observer.

In order to measure these two indicators of quality and relating them to the concept of PTL, we set up a number of experiments with one transmitter and one receiver placed at different distances. Both indoor and outdoor experiments were carried out. However, due to space limitations it is not possible to present here all the experiments performed, so we will just summarize the main results obtained.

Intuition says that the following two properties should be observed: (i) for a fixed transmission power, increasing the distance between Tx and Rx should reduce both PRR and LQI, and (ii) for a fixed distance, increasing the transmission power should increase both PRR and LQI.

Figure 6 shows the values measured in one set of experiments. This graph depicts six curves, one for each PTL used, in which it is possible to observe the PRR measured for different distances. As expected, the PRR decreases with the distance, and drops significantly faster when lower power transmission is used[1]. This confirms the initial intuition.

Nevetheless, the value of LQI does not present such a clear and predictable behavior. In experiments, we measured sudden drops of this value, caused by some physical phenomena that were hard to interpret. For instance, Figure 7 shows the LQI measured for each packet received during a certain experiment. It shows six curves again, one for each PTL. Random drops are noticeable for every PTL. These results are consistent with the literature about WSN, which indicate the existence of so called *grey areas* in which the quality of the communication signal experiences strong sudden variations [10]. According to our results, increasing the transmission power makes the grey area move further but does not eliminate it.

For determining whether the LQI drops actually represent a problem for the communication, it is necessary to study them on the light of the information provided by the PRR. For performing a comparison between these two parameters,

[1]The small increment observable at 140m with PTL=3 is a singularity that might be due to some kind of perturbance, probably during the experiment at 120m.

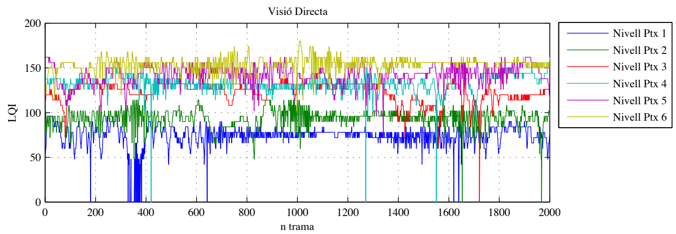


Figure 7. Measured LQI for each frame received (for the six PTL)

we define two measures: the average PRR after m packet receptions, calculated as $\frac{1}{m}\sum_{i=1}^{m}\mathrm{PRR}_i$; and the average LQI after m packets, calculated as $\frac{1}{m}\sum_{i=1}^{m}\mathrm{LQI}_i$. The comparison of these measures shows that, regardless of the PTL used, it is possible to find a low threshold for LQI, under which a good PRR cannot be guaranteed. But it also shows that over this threshold, the LQI is still a poor indicator of the link quality, especially when low power transmission is used. Although these results were obtained in very specific experiments and thus they are not conclusive, they provide insightful information about the role of power transmission and what a good indicator of the link quality could be.

V. Introducing PTL in the modeling of components: first steps

As indicated in the Introduction, the goal of our research is to find a mechanism based on RTI for relating the transmission power of the WSN nodes with the global quality of the system, what would make it possible to perform scheduling decisions that take both energy consumption and quality into consideration. Given that PTL mainly affects the quality of the communication, this means that the quality assumed for the links must be known in advance. This could be indicated for instance using PRR, although the question of which is the best indicator of link quality remains open.

Assuming that the lower bound for the quality of each link is known (we will denote it as PRR^l), then the following reasoning can be introduced in the RTI presented in [3].

If $\mathrm{PRR} > \mathrm{PRR}^l$ then PTL can be decreased in order to reduce energy consumption. If the energy consumed is reduced significantly, then an increment of the computation quality can be considered. The latter would be solved with some of the mechanisms for dynamic bandwidth allocation.

Conversely, if $\mathrm{PRR} < \mathrm{PRR}^l$ then the PTL should be increased. However, this increment should go through an admission test in order to determine if it exceeds the maximum energy allowed to the node/cluster. If such an energy increment is not possible, then the node must reduce its computation quality to a level such that the PTL can be increased without violating the energy constraints. However, this would cause a reduction of the load of the component that should then be treated with some of the mechanisms for dynamic load allocation, in order to guarantee that the best possible global quality is still maintained by the system.

VI. Conclusions

This paper represents a first step towards understanding the role that power transmission plays in the global quality of service of a WSN and how it can be effectively handled in order to reduce energy consumption. Our experiments show that, as expected, energy consumption may vary greatly depending on the chosen PTL. We have also studied which indicators can be used in order to determine the link quality during runtime, and although the results are not conclusive and need further research, we found out some properties of the Packet Receive Rate (PRR) and the Link Quality Indicator (LQI) that can be exploited for fulfilling this goal. Finally, we have sketched how this knowledge can be integrated with an already-existing technique for energy-aware global scheduling of resources in WSN based on Real-Time Interfaces.

References

[1] *IEEE Standard for Information Technology. Part 802.15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LR-WPANs)*, IEEE Std. 802.15.4, 2003.

[2] J. Polastre, R. Szewczyk, and D. E. Culler, "Telos: enabling ultra-low power wireless research," in *Proc. of IPSN*, 2005, pp. 364–369.

[3] L. Santinelli, M. Chitnis, C. Nastasi, F. Checconi, G. Lipari, and P. Pagano, "A component-based architecture for adaptive bandwidth allocation in wireless sensor networks," in *SIES*, 2010, pp. 174–183.

[4] E. Wandeler and L. Thiele, "Real-time interfaces for interface-based design of real-time systems with fixed priority scheduling," in *Proc. of the 5th ACM international conference on Embedded software (EMSOFT '05)*. ACM, 2005.

[5] B. Hohlt, L. Doherty, and E. Brewer, "Flexible power scheduling for sensor networks," in -, 2004, pp. 205–214.

[6] T. Kim, N. Park, P. K. Chong, J. Sung, and D. Kim, "Distributed low power scheduling in wireless sensor networks," in *Wireless Pervasive Computing, 2007. ISWPC '07. 2nd International Symposium on*, 2007.

[7] H. Aydin, R. Melhem, D. Mosse, and P. Meja-Alvarez, "Power-aware scheduling for periodic real-time tasks," in *Proc. of the 22nd Real-Time Systems Symposium*, 2001.

[8] *JN513x Wireless Microcontroller Datasheet, v.1.6*, Jennic Ltd. Datasheets, 2008.

[9] S. Y. Shin, S. Choi, H. S. Park, and W. H. Kwon, "Packet error rate analysis of ieee 802.15.4 under ieee 802.11b interference," in *Proc. Int. Conference on Wired/Wireless Internet Communications (WWIC2005)*, 2005.

[10] J. Zhao and R. Govindan, "Understanding packet delivery performance in dense wireless sensor networks," in *Proc. 1st ACM Conf. Embedded Network Sensor Systems*. 1–13, 2003.