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Article

Performance Comparison of a Novel Adaptive Protocol with the Fixed Power Transmission in Wireless Sensor Networks

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Abstract: In this paper, we compare the performance of a novel adaptive protocol with the fixed power transmission protocol using experimental data when the distance between the transmitter and the receiver is fixed. In fixed power transmission protocol, corresponding to the distance between the sensor and the hub, there is a fixed power level that provides the optimal or minimum value in terms of energy consumption while maintaining a threshold Quality of Service (QoS) parameter. This value is bounded by the available output power levels of a given radio transceiver. The proposed novel adaptive power control protocol tracks and supersedes that energy expenditure by using an intelligent algorithm to ramp up or down the output power level as and when required. This protocol does not use channel side information in terms of received signal strength indication (RSSI) or link quality indication (LQI) for channel estimation to decide the transmission power. It also controls the number of allowed retransmissions for error correction. Experimental data have been collected at different distances between the transmitting sensor and the hub. It can be observed that the energy consumption of the fixed power level is at least 25% more than the proposed adaptive protocol for comparable packet success rate.

Keywords: wireless sensor network; adaptive power control; energy efficiency

1. Introduction

The proliferation of low power wireless sensor networks (WSNs) and their discreet presence have introduced a new paradigm in data collection and analysis of target parameters in both indoor and outdoor environments. This has been differently named in the literature and the industry, like 'invisible", "pervasive", or "ubiquitous" [1] computing. Others prefer to refer to it as "ambient intelligence" [2]. The broad idea is that there will be sensors that are able to exchange information with a certain base station or hub and perform an assigned task. The sensors, the computational and the communication units, along with the hub, form the ubiquitous sensor network (USN). The term ubiquitous is applied to the collection and utilization of information in real time, at anytime and anywhere. The technology has enormous potential and a wide range of applications, especially in environmental monitoring, health monitoring for assisted living (smart home environments) and industrial and plant monitoring (industrial automation). Most of these sensors are battery powered and therefore have limited operational lifetime before they are replaced with new batteries. Replacement of batteries in hundreds of sensors is a continuous and cost prohibitive undertaking. The cost of the batteries themselves is a small fraction of the overall costs; the storage, handling and labour costs being much more. Additionally, there are costs associated with the disruption caused to the sensor network which can be significant in a critical application. Over the life of the sensor it can be a substantial expense, dramatically eroding the ROI (return of investment) of wireless sensor deployments [3]. ON World estimates the labour cost for changing batteries in wireless sensors will be greater than $1 billion over the next several years, assuming no energy-harvesting methods are used [4]. The network disruption and cost of battery replacement are significant factor constraining the growth of wireless sensor networks. It is therefore, important to design intelligent power saving algorithms to extend the lifetime of sensor nodes and reduce the overall operational cost of wireless sensor networks.

2. Related Work in Power Saving Algorithms

Power saving approaches can be broadly classified into media access control (MAC) layer solutions and network layer solutions [5]. The role of MAC layer is to control when and how each sensor node can transmit in the wireless channel. An energy efficient MAC protocol is meant to

- Reduce collisions
- Reduce idle listening
- Avoid overhearing
- Reduce control packet overhead

In contrast to MAC layer solutions, the network layer solution adjusts the appropriate transmission parameters to achieve power saving. The transmission parameters that may be tweaked are:

- Transmission power
- Modulation technique
- Data rate

In this paper, we have investigated different transmission power control algorithms for wireless communication as network layer solutions to achieve energy efficiency. In general, the existing energy efficient power control algorithms use channel side information (CSI) like the RSSI or the LQI for channel estimation and to modulate the output power. The next section discusses the RSSI/LQI based output transmission power control protocols.

RSSI/LQI Based Power Control Algorithms for Energy Efficiency

RSSI is a measurement of signal power and is averaged over first 8 symbols of each incoming packet [6]. On the other hand, LQI is usually vendor specific and is measured as a score between 50 and 100 based on the first eight symbols of the received packet [7]. The RSSI/LQI based power control approaches are guided by the closed loop control mechanism between the transmitting node and the receiving base station. The general steps are described below as

- The transmitter sends packet at an updated power level to the receiver
- Receiver measures the RSSI /LQI
- If the RSSI/LQI is below the threshold that is required for faithful packet delivery, then the receiver sends the control packet at the new transmission power level.
- At the transmitter, the control packet is received and the current power level is updated for packet delivery

During initial communication set up phase, the transmitter needs to know the power level at which it should transmit to successfully deliver the packet. In this phase, the transmitter sends several packets at all its available power levels. In return, it receives RSSI values for each power levels. Based on the mapping between the RSSI and the output power level, the transmitter selects the required power level. Shan Lin *et al.* [6] have introduced an adaptive transmission power control (ATPC) that maintains a neighbour table at each node and a feedback loop for transmission power control between each pair of nodes. ATPC is the first dynamic transmission power algorithm for WSN that uses all the available power output levels of CC2420 [8]. In this adaptive transmission power protocol, the neighbour table contains the proper transmission power level that this node should use for its neighbour and the parameters for a linear predictive model. The idea of this predictive model is to use a function that approximates the distribution of RSSI at different transmission power levels and to adapt to any change in radio link quality over time. The aim of ATPC is to determine the minimum power level to maintain a satisfactory link quality between two neighbouring nodes. Practical-TPC [9] is a receiver oriented protocol that is considered robust in dynamic wireless environments and uses packet reception rate (PRR) values to compute the transmission power that should be used by the sender in the next transmission attempt. While ATPC uses all 32 power levels, there are some algorithms that divide these 32 power levels into eight levels, as presented in [5]. The work that is presented in this research paper aims to avoid the need for such probe packets and their associated energy cost.

ART (Adaptive and Robust Topology control) protocol [10] has been designed for complex and dynamic radio environments. It adapts the transmission power in response to the variation in link quality or the degree of contention. Analysis of the paper has suggested that RSSI and LQI may not be good or the most reliable indicators of link quality, especially in dynamic indoor radio environment. The algorithm in paper [5] also has an initialization phase and a maintenance phase while adjusting transmission power. In the initialization phase, each of the sensor nodes uses the eight power levels of

CC2420 to send 100 probe packets in each of the power levels. It sets the packet delivery ratio (PDR) threshold to 80% instead of the RSSI threshold to determine the minimum power level at which the nodes must communicate with each other. In the maintenance phase, the aim is to adjust the transmission power level with the changing environment.

REAL (reliable energy adept link-layer) protocol uses an error correction mechanism to maintain reliable communication [11]. It chooses its data recovery strategy based on the overall information distortion and the available energy at a sensor node. The data recovery actions have three options to choose from. They are

- Use of error correction code to recover the original data packet at the receiver
- Retransmit when the error correction mechanism has failed due to severe distortion
- Drop some packets to save energy for transmission of higher priority packets

In [12], the approach is similar to ATPC where the power-distance table is maintained at each node. The minimum transmission power of one node with the neighbouring node is considered as the 'distance' and packets will be routed through these nodes in a multihop sensor network topology. Therefore, the optimization of the transmission power is the shortest path problem based on the power-distance relationship. This algorithm relies on broadcast-and-feedback mechanism to determine the minimum transmission power required for each neighbouring node. This algorithm can optimize power consumption by choosing to transmit via one or multi-hop. In [13], the authors have proposed a power control algorithm in which each sensor node also uses beacon messages to discover its neighbours to communicate with and the corresponding minimum transmission power. After the neighbours are discovered, the adaptive algorithm finds the optimal power so that it is able to meet its target of communicating with a given number of neighbouring nodes. In paper [14], the authors have introduced the term "link inefficiency" while characterizing the link quality metrics of energy constrained wireless sensor nodes. Link inefficiency is defined as the inverse of the packet success probability as it represents the mean number of transmissions for a successful transmission at a given time. The expected energy consumption is therefore proportional to the link inefficiency. This paper proposes the time-averaged energy consumption as the cost metrics.

The application of an adaptive power control algorithm for IEEE 802.11 in the technical report of [15] aims to modulate the transmit power to the minimum level based on the distance between the communicating nodes, such that the destination node still achieves correct reception of a packet despite intervening path loss and fading. It used a radio module with a configurable output power level (0 to 25 dBm). The receiver only sends the control packet containing the optimal transmission power level when there are significant changes in the RSSI values.

It can be inferred from the above discussion that the RSSI/LQI based adaptive power control algorithms are attractive options to save energy. It is worth noting that these algorithms are mainly designed for multi-hop network where each sensor node broadcasts beacon packets and discovers its neighbour to which it is able to transmit at minimum power. However, there are two factors that are worth considering. They are

- The initial overhead cost for building up the RSSI vs. Power level table.
- In case the sensor is mobile, the frequency of refreshing the table becomes crucial and that also adds up to the cost.

- Determining the ideal channel sampling frequency for link quality estimation that would optimise energy efficiency. It has been suggested that in general sampling once every 24 h is sufficient to track channel link quality. However, indoor radio channels are dynamic and link quality can vary widely over a period of 24 h and such a sampling rate may fail to capture the temporal dynamics of the radio channel [6].

In GSM (Global System of Mobile Communications), power control algorithm is employed to achieve desired signal strength for faithful communication between the mobile station (MS) and the base transceiver station (BTS). Power control also reduces interference and improves cell capacity. During a connection between the BTS and the MS in a cell, the MS measures the channel RF link quality after every 480 ms [16]. In this way an acceptable link quality is maintained which can also improve the battery lifetime of the mobile device. The drive for small and discreet sensors has prompted the use of coin cell batteries with capacity in the order of 250–300 mAh [17]. Their capacity is far less as compared to those that are used in mobile phones (~1500–3500 mAh) [18–20]. This link quality measurement and maintenance method will rapidly deplete the sensor battery even at a lower rate, primarily because of the limitation of the capacity of these batteries used in wireless sensors.

Section 2 has discussed the different channel estimation methodologies and power control approaches to save energy of the wireless sensor nodes. In general, these algorithms use link quality information (RSSI or LQI) for adjusting the output power. Some of them also use probe or beacon packets for link quality estimation. Overall, some form of communication is required between the nodes before actual packet can be transmitted. The more often the nodes communicate, the faster they will be depleted of energy. The proposed novel non-RSSI/LQI based adaptive power control algorithm has a unique channel estimation method without RSSI side information. It also does not send probe packets before the actual data packet transmission. Section 3 describes the new algorithm in details.

3. Non-RSSI/LQI Based Channel Estimation and Power Control Algorithms for Energy Efficiency

The initial outline of the novel non-RSSI based channel estimation and output power control algorithm was proposed by us in [21]. The hardware platform (RF transceiver module) that is used to conduct the experiments is nRF24L01p from Nordic semiconductors [22]. The radio transceiver module has four programmable output power levels that do not provide RSSI information. The output power modes and their current ratings are presented in Table 1.

Table 1. Operational modes and current consumptions of NRF24L01p.

Operational Mode	Current Consumed (mA)
Transmission @ −18 dBm output power (MIN)	7
Transmission @ −12 dBm output power (LOW)	7.5
Transmission @ −6 dBm output power (HIGH)	9
Transmission @ 0 dBm output power (MAX)	11.3

As expected, it can be seen from Table 1 that the transceiver consumes maximum current at the highest output transmission power of 0 dBm. Interestingly, the current consumptions at the different power levels do not scale proportionally with the output power levels. The current consumption almost halves when the output power level drops almost 100 times from 0 dBm to −18 dBm. This feature is common among existing low power wireless transceivers that have programmable output power levels. Noted among them are CC2420 [8] and CC2500 [23] from Texas instruments. The output power vs. current consumption behaviour in CC2420 is almost the same as nRF24L01p. In CC2500, the current consumption almost halves when the output power level drops approximately 20 times from +1 dBm to −12 dBm. This kind of disproportionate output power vs. current consumption characteristics poses stiff challenges in developing power control algorithms.

The basis of this lightweight adaptive algorithm is the states where each state represents one cycle of packet transmission. Figure 1 shows the state transition diagram of the adaptive power control algorithm. State transition occurs depending on the power level at which the transmission is successful or has failed.

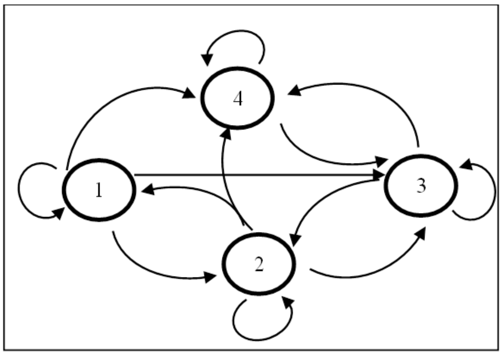

Figure 1. State transition diagram of the adaptive algorithm.

The objective of the adaptive power control algorithm is to respond to the packet error rate and move to a new state with different retry limits. The adaptive algorithm is designed in such a way that it takes into account the performance in each state. Each state has a different retry limit. Increasing state number indicates poorer channel quality. The proposed adaptive algorithm does not allow retransmission in the same power level except when it is in state 4 and transmitting at 0 dBm. When the system is in state 4, it is considered the worst channel condition and three retries are allowed. The retry limit of state 1 is three. However, the retry limit of states 2 and 3 have been set at 2 and 1. The asymmetry is because the increase in the retry limit in states 2 and 3 can increase the current consumption while only marginally improving the packet success rate.

Table 2 shows the available power levels based on the states. Transmission starts at the lowest available power level of that particular state. The transmitter can be in any one of the states during the start of transmission of a packet. There are two separate algorithms that determine the state transitions, one from a lower state to higher state and the other from a higher to lower states. The logic to transit to lower states also includes situations when it remains in the same state or transit to a lower state.

Table 2. States, power levels, and retry limits.

State	1	2	3	4
Available power levels	Minimum (M) Low (L) High (H) Maximum (X)	Low (L) High (H) Maximum (X)	High (H) Maximum (X)	Maximum (X)
Number of retries	3	2	1	3

Table 3 describes the state transition matrix when state level goes up. All the state transition decisions depend on the success or failure of the packet being transmitted to the destination hub.

Table 3. State transition matrix when state levels go up.

		Next State			
		1 (MLHX)	**2 (LHX)**	**3 (HX)**	**4 (X)**
Current State	1 (MLHX)	Succeed at level M	Succeed at level L	Succeed at level H	Failed or Succeed at level X
	2 (LHX)	Not applicable	Not applicable	Succeed at level H	Failed or Succeed at level X
	3 (HX)	No transition	Not applicable	Not applicable	Failed or Succeed at level X
	4 (X)	No transition	No transition	Not applicable	Not applicable

Table 4 describes the state transition logic when state level goes down. The primary objective of the adaptive algorithm is to save energy by transmitting at a power level that is enough to send the packet successfully through the channel. For example, when the system is in state 4, it is transmitting at the maximum power. With time, the channel condition can improve and packet can be successfully transmitted at a lower power level. If the system drops down to state 3, the transmission starts at a lower power level. This drop-off from a higher state to a lower state is determined by a drop-off algorithm which is probabilistic in nature.

Table 4. State transition matrix when state levels go down.

		Next State			
		1 (MLHX)	**2 (LHX)**	**3 (HX)**	**4 (X)**
Current State	1 (MLHX)	Success at state M	Not applicable	Not applicable	Not applicable
	2 (LHX)	Probabilistic model that depends on the number of successes in level L	Probabilistic model that depends on the number of successes in level L	Not applicable	Not applicable
	3 (HX)	No transition	Probabilistic model that depends on the number of successes in level H	Probabilistic model that depends on the number of successes in level H	Not applicable
	4 (X)	Not applicable	Not applicable	Probabilistic model that depends on the number of successes in level X	Probabilistic model that depends on the number of successes in level X

In the proposed adaptive algorithm, the drop-off or the back-off process is dependent on the number of successes (S) in the higher power level and a drop-off factor (R). By default, the drop-off factor is 1. The probability of the system to drop-off to a lower power level is represented by Equation (1).

$$P_{drop-off} = 1 - e^{(-RS)} \tag{1}$$

Here, $P_{drop\text{-}off}$ = probability of drop-off

S = THE NUMBER OF SUCCESSES IN THAT POWER LEVEL OF THE HIGHER STATE

R = DROP-OFF FACTOR

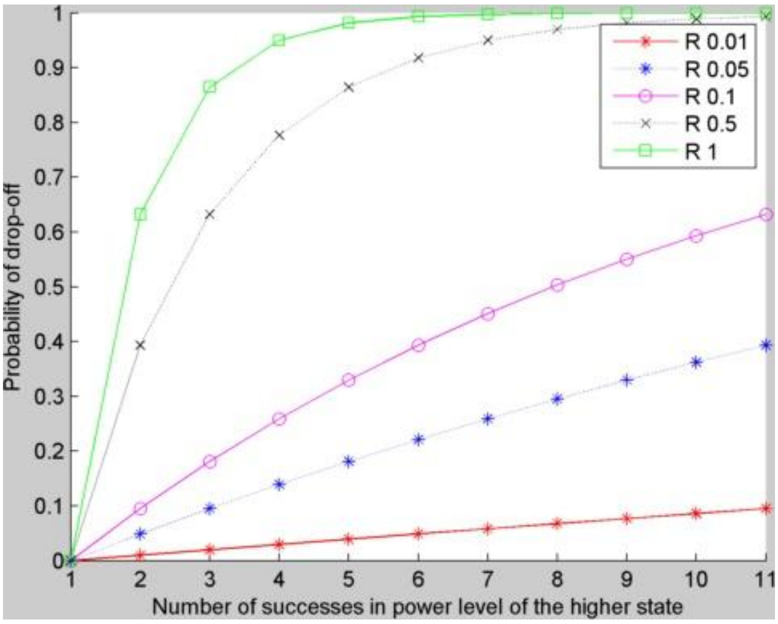

Figure 2. The curves behave differently depending on the value of R. A low R value indicates slow back off while a high R indicates fast back off. When the number of successes is 0, the probability of transition is 0. This drop-off algorithm takes into account of all the previous successes indicating that it also uses past history while dropping-off.

The plots in Figure 2 show the state transition probability based on different values of R. When there is a state change, the value of S is reset to 0.

Overall, the value of R indicates as to how fast the system will fall from a higher state to a lower state. When there is no success, the probability of state transition is 0, meaning that there will be no state transition. At the same time, when the number of successes is too high, it converges to 0.

Back-off algorithms are extensively used in data communication (both wired and wireless) by MAC protocols to resolve contention among transmitting nodes to acquire channel access. In a MAC protocol, the back-off algorithm chooses a random value from the range [0, CW], where CW is the contention window size. The contention window is usually represented in terms of time slots.

The number of time slots to delay before the *n*th retransmission attempt is chosen as a uniformly distributed random integer r in the range $0 < r < 2^k$.
Where $k = \min(n, 10)$, 10 is the maximum number of retries allowed.

The *n*th retransmission attempt also means that there have been *n* collisions. For example, after the first collision, it has to retransmit. Based on the back-off algorithm, the sender will choose between 0 and one time slot for the retransmission. After the second collision, the sender will wait anywhere from 0 to three time slots (inclusive). After the third collision, the senders will wait anywhere from 0 to seven time slots (inclusive), and so forth. As the number of retransmission attempts increases, the number of possibilities for delay increases exponentially [24,25].

Similarly, an exponential operator is used in this novel adaptive algorithm to decide to switch from a higher state to a lower state. The drop-off algorithm is dynamic as it re-evaluates at every successful transmission. It gets reset to 0 when it leaves the state and jumps to a lower state and starts a new packet transmission at a lower power level.

In each state there are output power levels in increasing order which can be used by the transmitter. There is no direct transition from state 4 to state 1 or 2. Similar conditions hold true when transiting from 3. It is guided by the drop-off factor R. In this paper, R values of 0.01, 0.05, 0.1, 0.5 and 1 are used. Higher value of R means higher rate of drop-off or the system will switch to a lower state faster. When R is 1, the probability of switching to a lower state increases rapidly with the number of successes (from no probability of transition at single success to 90% probability after three successes in Figure 2). Whereas, when R is set at 0.01, the change in probability is slow. The probability of transition or switch changes from 0 to less than 5% after three successes.

4. Performance Parameters

The performance parameters are:

- Average cost per successful transmission
- Expected success rate or protocol efficiency [26]

One of the parameters for the optimization is the energy consumed per useful bit transmitted over a wireless link [5,26]. Similarly in this paper, the cost per successful transmission has been considered.

$$C_{S\_avg} = \frac{C_T}{P_S - P_L} \tag{2}$$

where, C_{S_avg} = average cost of successful transmission

C_T = total cost of transmission

P_S = total packets to send

P_L = number of lost packets

All cost values are measured in mJ. The total cost of transmission includes the expenditure for the first transmission attempt of a packet and the subsequent retries if the first attempt fails. The count of the total packet-to-send does not include the retry packets. Therefore the denominator in Equation (3) is the count of successfully transmitted packets.

The expected success rate or efficiency is defined as the expected number of successes and takes into account the average number of retries [5]. It can also be defined as the expected number of successes per 100 transmissions. Mathematically,

$$Succ_{rate} = \frac{P_S - P_L}{P_S + Ret_T} \tag{3}$$

where $Succ_{rate}$ = expected success rate

Ret_T = total number of retries

Here $P_S - P_L$ = total number of successes ($Succ_T$)

If both the numerator and denominator are divided by P_S, then in percentage term

$$Succ_{rate}\,(\%) = \frac{PSR}{1 + Ret_{avg}} \tag{4}$$

where Ret_{avg} = average number of retries per packet

$$Ret_{avg} = \frac{Ret_T}{P_S} \tag{5}$$

$$PSR = \frac{P_S - P_L}{P_S} \times 100 \tag{6}$$

where, Ret_T = total number of retries

$Succ_{rate}$ indicates the total number of transmissions (on average) to achieve a given packet success rate (PSR). It also indicates the efficiency of the adaptive protocol because the lower the average number of retries per packet, the higher the value of the expected success rate for a given PSR (Equation (4)).

5. Experimental Setup

The objective of the experiments is to compare the performance parameters of the proposed adaptive power control algorithm with fixed power transmission in indoor radio environment by fixing the distance between the transmitting node and the hub. At different positions, the PSR, the protocol efficiency and the average energy expenditure are evaluated and compared. Experiments were conducted inside a University building and in a house where a gathering of people was held. Experiments 1 to 4 and 6 were conducted during the busy hours. Experiment 5 was conducted during the non-busy hours.

In general, the radio signal suffers from fading because of multipath propagation where the radio signal from the transmitter arrives at the receiver through multiple paths. During the busy hour, there are lots of movements of people in between the hub and the transmitting sensor. These movements induce a time varying Doppler shift on multipath components. Fading effect due to frequency shift of the radio signal cannot be ignored when the sensor is stationary. Besides, there can be temporary signal attenuation if people have gathered around. All these affect the radio link quality over time. During the non-busy hours of the University, fading effect due to movement is minimal while the multipath effect still exists [27]. The objective of the experiments was to observe how busy hour performances are different from non-busy hour performances.

The nRF24L01p module has four discrete power levels. They are −18 dBm, −12 dBm, −6 dBm and 0 dBm. In order to compare the performance criteria of adaptive protocol with the fixed power transmission, during each transmission instance, a total of nine packets were sent. They are:

- Four packets at power levels −18 dBm, −12 dBm, −6 dBm and 0 dBm
- Five packets at power levels determined by the drop-off rates (R) 0.01, 0.05, 0.1, 0.5 and 1 of the proposed adaptive protocol

We have allowed three retries in each of the fixed power level to bring parity with the adaptive protocol where three retries are allowed in state 1 and 4.

The code for the adaptive protocol and the fixed power transmissions are all written in C and downloaded in the nRF24L01p modules and the sensors. Before the performance parameters are compared, it is important to understand the factors that influence the cost in fixed power mode.

6. Factors Affecting the Average Cost in Fixed Power Mode

The average cost of successful transmission is determined by three factors as shown in Equation (6).

$$C_{S\_avg} = \frac{C_p * (1 + Ret_{avg})}{PSR} \tag{7}$$

where C_p = cost of one transmission at a particular power level

Therefore the three factors are:

- Energy used to transmit one packet (C_p)
- Average number of retries (Ret_{avg})
- Total number of successes ($P_s - P_L$)

The energy used per packet transmission increases with the output power level. Table 1 summarises the current rating in each of these power levels of nRF24L01p. On the other hand, the average retries in each of these levels decreases and the PSR increases with the increase in power level.

7. Experimental Results and Analysis

In this section, the experimental results are analysed.

Experiment 1

Distance between the Sensor and the Hub	Number of Wall Type I: Light Internal Walls (Plasterboards)	Number of Wall Type II: Internal Walls (Concrete, Bricks)
14 m	5	0

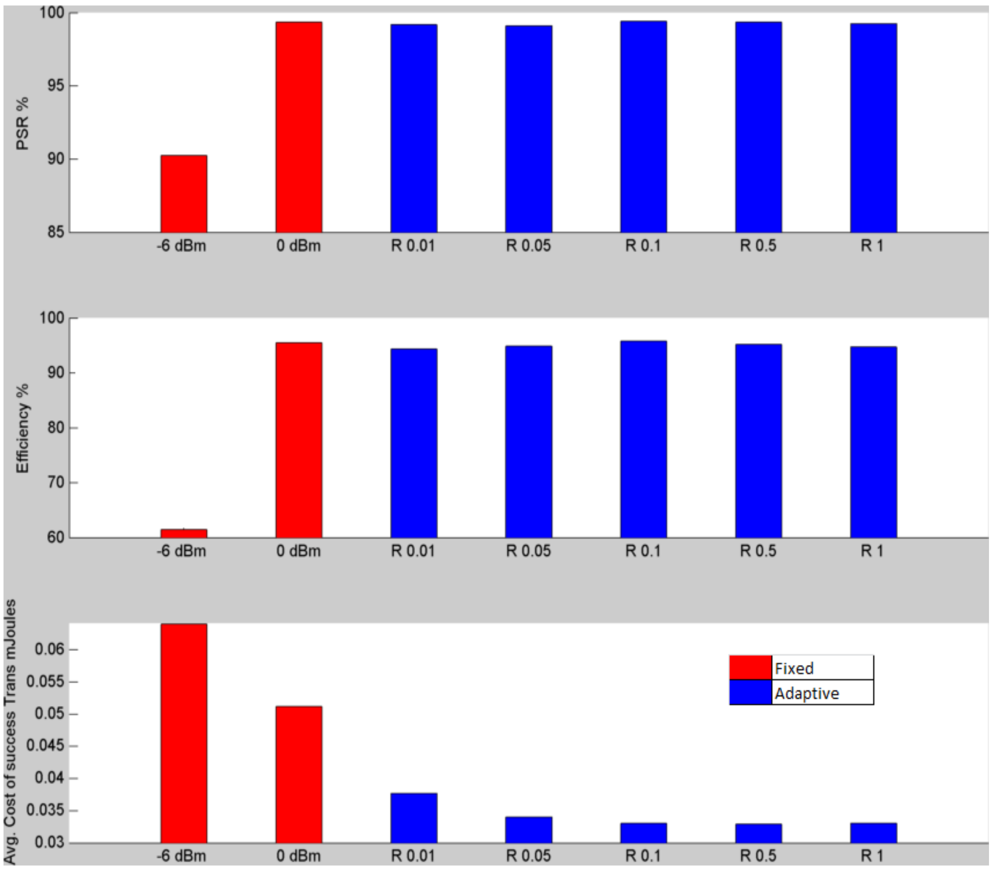

Figure 3. Comparison of the PSR, efficiency, and average cost of successful transmission when the distance between the sensor and the hub is 14 m. The minimum cost at fixed power is achieved at 0 dBm. The PSR of fixed power at 0 dBm is almost similar to the PSRs of the adaptive protocol. The adaptive protocol consumes 55% less energy than at 0 dBm when value of R is 0.5.The efficiency of the fixed power transmisison (0 dBm) is a touch higher than the adaptive protocol at R = 0.5.

The primary reason to include the two wall types is that a radio signal suffers different levels of attenuation when it passes through these walls in an indoor environment. The wall type I accounts for 3.4 dB signal loss per wall, while the wall type II accounts for 6.9 dB loss per wall. These wall types are mentioned in the standards and the Cost231 path loss model for indoor operations above 900 MHz is widely used [28]. This model takes into account the losses due to two different types of walls within a building and between floors. It is therefore important to include the effect of these types of partitions when the adaptive algorithms are analysed.

Figure 3 shows that the proposed adaptive algorithm can save 55% energy as compared to fixed power transmission when the value of R is 0.5. The minimum cost fixed cost was achieved at 0 dBm. However there is not much difference in the costs with other R values. The PSR of −18 dBm and −12 dBm are not included in the plot as they are too low. The indoor radio propagation mechanism is complex as it has multipaths, fading effects, and propagation of radio waves through walls.

Experiment 2

Distance Between the Sensor and the Hub	Number of Wall Type I: Light Internal Walls (Plasterboards)	Number of Wall Type II: Internal Walls (Concrete, Bricks)
18 m	4	0

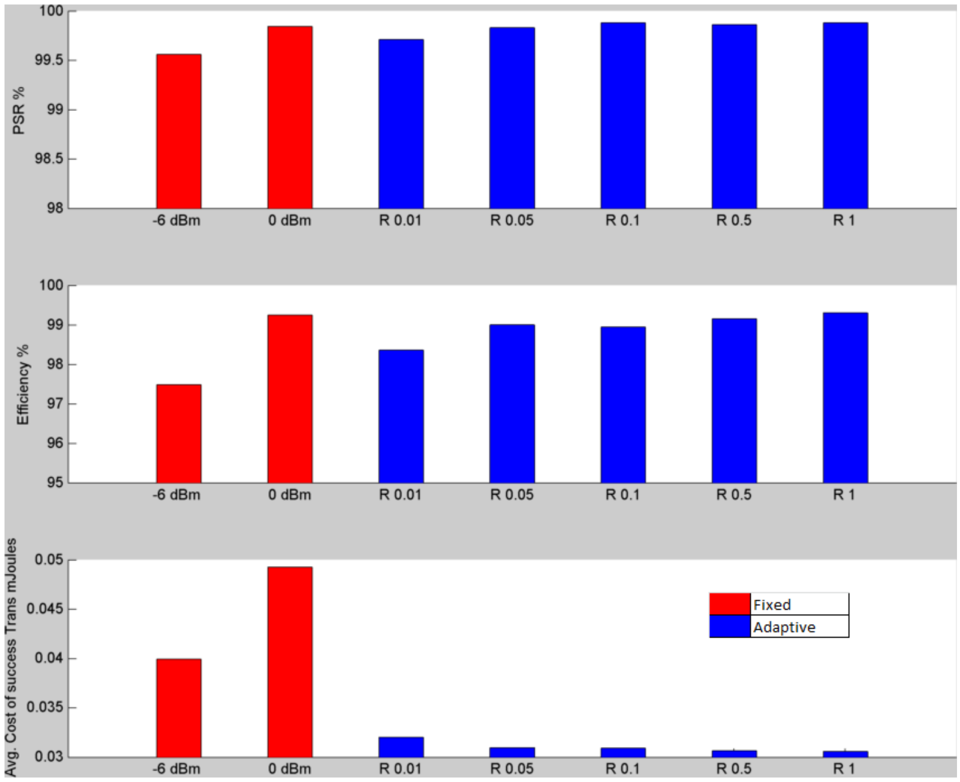

Figure 4. Comparison of the PSR, efficiency and average cost of successful transmission when the distance between the sensor and the hub is 18 m. The minimal cost of fixed power transmission is achieved at –6 dBm. The minimum energy consumption is at −6 dBm, primarily because of similar PSR and efficiency as at 0 dBm. In terms of energy efficiency, the adaptive protocol consumes 30% less energy than the fixed power transmission at −6 dBm when R is 1. The efficiency of the adaptive protocol at R = 1 is higher than fixed power transmission at –6 dBm.

Figure 4 plots the PSR, efficiency and cost values when the distance is 18 m. The optimal cost at fixed power transmission is at −6 dBm. This is because of almost similar PSR and efficiency values as at 0 dBm. There are four wooden partitions in between the transmitter and receiver. The adaptive protocol consumes 30% less energy than the fixed power transmission at −6 dBm when R = 1.

Although the distance in experiment 1 is less than that in experiment 2, due to an extra partition in experiment 1, the average signal attenuation is more and contributed to a lower PSR than that in experiment 2.

Experiment 3

Distance Between the Sensor and the Hub	Number of Wall Type I: Light Internal Walls (Plasterboards)	Number of Wall Type II: Internal Walls (Concrete, Bricks)
20 m	4	0

Figure 5 shows that the application of adaptive protocol can consume up-to 55% less energy than when fixed power transmission is used. There are four wooden partitions in between the transmitter and receiver.

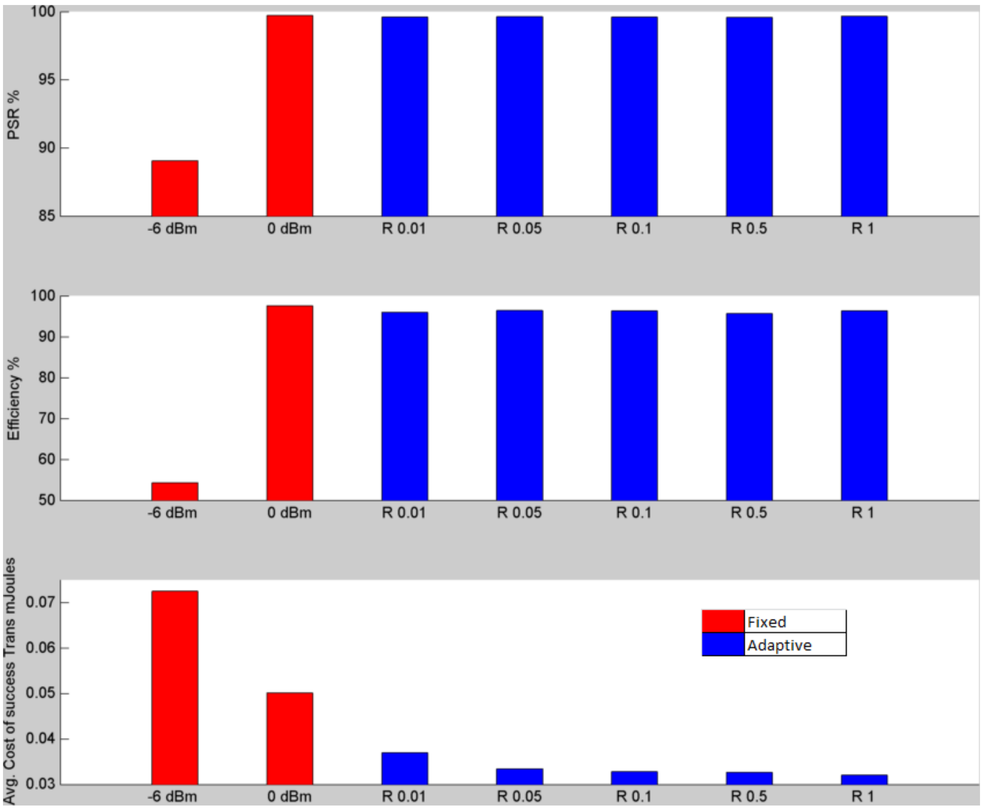

Figure 5. Comparison of the efficiency and average cost of successful transmission based on the PSR when the distance between the sensor and the hub is 20 m. The minimal cost of fixed power transmission is achieved at 0 dBm. In this case the PSR of fixed power at 0 dBm is same as the PSRs of adaptive protocol. In terms of energy efficiency, the adaptive protocol consumes 55% less energy than the fixed power transmission at 0 dBm when R = 1. The efficiency of the fixed power transmisison is a touch higher than that of the adpative protocol at R = 1.

Although the current consumption at −6 dBm is less than that at 0 dBm, due to lower PSR, it is not able to compensate for the cost. The efficiency of the adaptive protocol is touch higher than fixed power transmission. The minimum energy consumption of fixed power is achieved at 0 dBm, primarily because it has much higher PSR and efficiency than at −6 dBm. In terms of energy efficiency, the adaptive protocol consumes 55% less energy than the fixed power transmission at 0 dBm.

Experiments 4 and 5

Distance Between the Sensor and the Hub	Number of Wall Type I: Light Internal Walls (Plasterboards)	Number of Wall type II: Internal Walls (Concrete, Bricks)
24 m	4	0

In this experiment, two sets of data were collected by fixing the position of the transmitter and the receiver during the busy hour and the non-busy hours of the University respectively.

Busy Hour Data

Figure 6 shows that the minimum energy consumption of fixed power is achieved at 0 dBm, primarily because it has much higher PSR and efficiency than at −6 dBm. The adaptive protocol consumes 6% less energy than the fixed power transmission at 0 dBm when R = 0.5. The efficiency of the fixed power transmission at 0 dBm is a touch higher than that of adaptive protocol at R = 0.5.

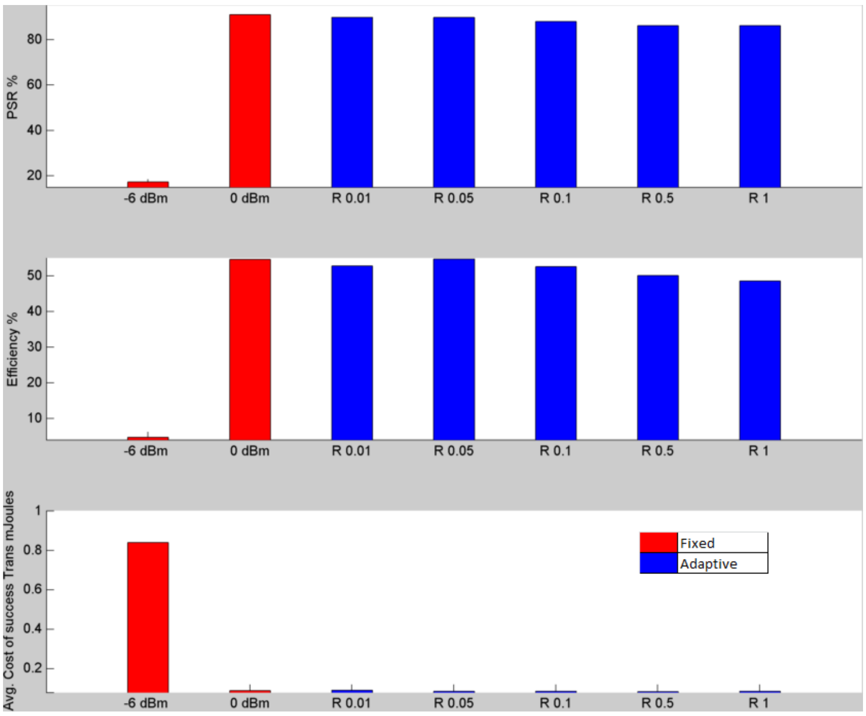

Figure 6. Comparison of the efficiency and average cost of successful transmission based on the PSR when the distance between the sensor and the hub is 24 m and collected during the busy hour. The minimum energy consumption of fixed power is achieved at 0 dBm, primarily because it has much higher PSR and efficiency than at −6 dBm. The adaptive protocol consumes 6% less energy than the fixed power transmission at 0 dBm when R = 0.5. The efficiency of the fixed power transmisison at 0 dBm is a touch higher than that of adpative protocol at R = 0.5.

The minimum energy consumption of fixed power is achieved at 0 dBm, primarily because it has much higher PSR and efficiency than at −6 dBm.

Figure 7 shows the comparison of the efficiency and average cost of successful transmission based on the PSR when the distance between the sensor and the hub is 24 m and collected during non-busy hours. The minimum energy consumption of fixed power is achieved at 0 dBm The adaptive protocol consumes 29% less energy than the fixed power transmission at 0 dBm when R = 1 The efficiencies of the adaptive protocol (at R = 1) and fixed power transmission (0 dBm) are comparable.

It can be concluded from the results of Figures 6 and 7 that there is a significant difference in performances between busy and non-busy hours of a day. It also demonstrates the fact that radio link quality can widely vary over time. The adaptive protocol is able to track the variation in link quality and save energy, thereby extending the operational lifetime of the battery.

Non-Busy Hour Data

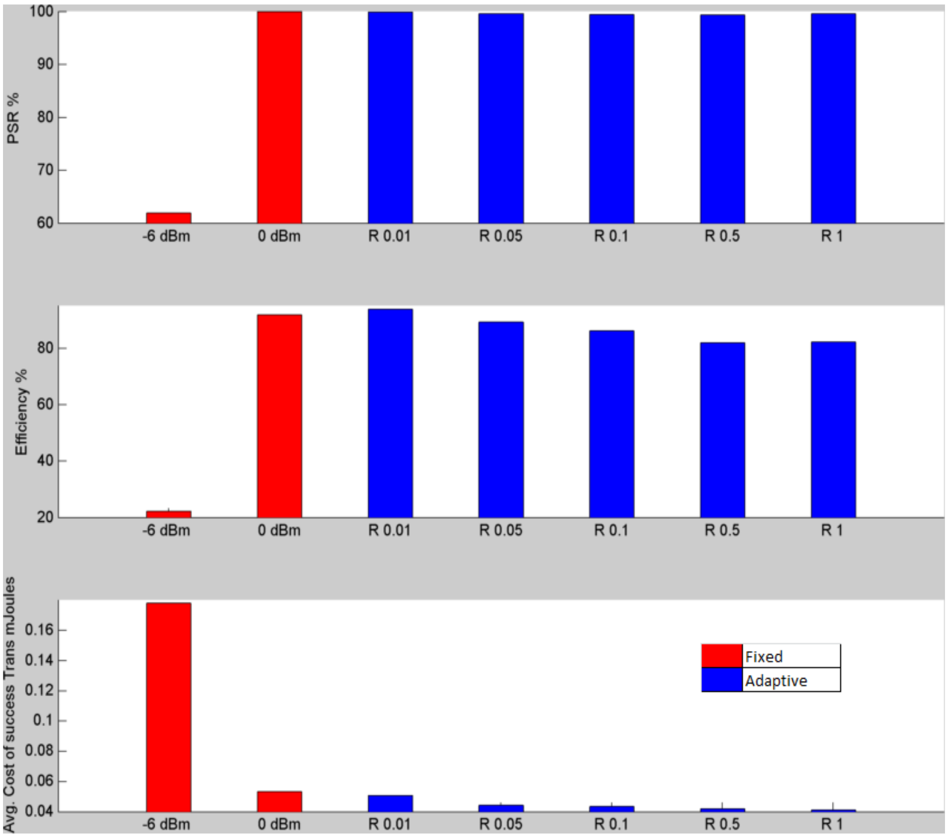

Figure 7. Comparison of the efficiency and average cost of successful transmission based on the PSR when the distance between the sensor and the hub is 24 m and collected during non-busy hours. The minimum energy consumption of fixed power is achieved at 0 dBm The adaptive protocol consumes 29% less energy than the fixed power transmission at 0 dBm when R = 1 The efficiencies of the adaptive protocol (at R = 1) and fixed power transmission (0 dBm) are comparable.

Experiment 6: Data collected from a house with a large gathering of people

Distance Between the Sensor and the Hub	Number of Wall Type I: Light Internal Walls (Plasterboards)	Number of Wall type II: Internal Walls (Concrete, Bricks)
15 m	3	1

There were around 20 people and a lot of movements, mainly because of the children around. This is also a busy hour scenario when the radio signal suffers from time-varying attenuation and wide flucation of signal over a short period of time.

The results of this experiments are shown in Figure 8. The overall energy saving is 26% when the adaptive protocol is used. The adaptive protocol has fared better because it has the ability to track the link quality even without any RSSI side information and switch to different states in response to packet lossses. At the same time, the intelligent design of the algorithm also allows it to switch back to a lower level state and transmit a new packet at a low power level.

The results of experiments 1 to 6 have shown the ability of the adaptive algorithm to make use of all the available power levels to successfully transmit a packet with fewer number of retries. Since in fixed power transmission there is no scope of output power level maneuvering, a large amount of energy may be wasted. Overall it can be concluded that the adaptive protocol can contribute significantly to energy saving of battery powered wireless sensors by adapting its output power.

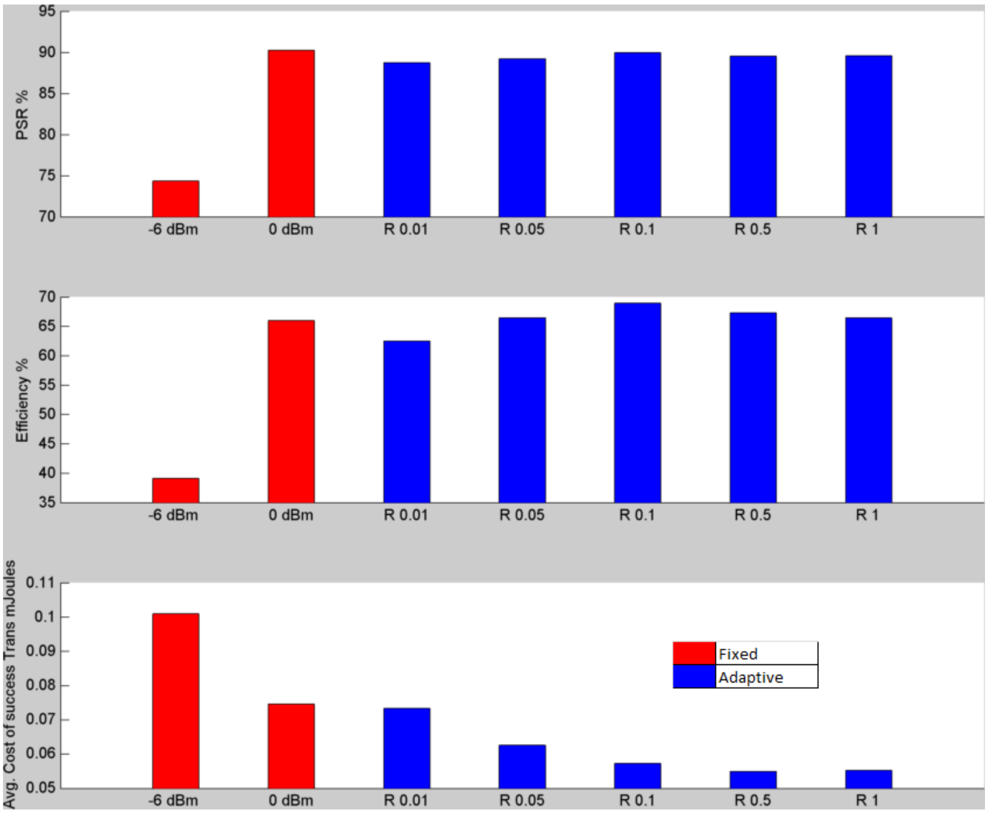

Figure 8. Comparison of the efficiency and average cost of successful transmission based on the PSR and data collected during a gathering in a house. The minimum energy consumption of fixed power is achieved at 0 dBm. In terms of energy efficiency, the adaptive protocol consumes 26% less energy than the fixed power transmission at 0 dBm when R = 0.5. The protocol efficiencies of both fixed (at 0 dBm) and adaptive R = 0.5) are the same.

8. Conclusions and Future Work

The results of this paper demonstrate that the non-RSSI based adaptive power control protocol can achieve significant energy savings as compared to fixed power solution. The drop-off factor (R) is an important parameter in the adaptive algorithm as it determines how fast the system will switch back to a lower state to transmit at a lower power. The experimental data show that the value of R can be set in between 0.5 and 1 to achieve optimal energy consumption. A low value of R means that the system will switch back to a lower power level slowly. Therefore in scenarios when the system has switched to a higher state level in response to momentary drop in signal level, a low R value means that even if the channel condition improves, the system will come down to lower state level slowly. Hence, the energy cost may rise. On the other hand, if R is set at 1, it will drop fast. But if the link quality change is not transient, the system will oscillate between the states. The experiments that were conducted have covered some common indoor radio channel scenarios. For future work, different R values can be set in the different states and the experiments repeated. The R values should be distributed in such a manner that the system can drop-off fastest when in the highest state level and gradually becomes slower with lower state levels in order to create a balance between switching up and switching down between states. A further extension of the research is to design and implement an algorithm such that the R value can be made adaptive. The system will constantly track the PSR and increase or decrease the R value. Overall, the results that are presented in this paper show that it is possible to track link quality without regular channel scanning and avoiding probe packets for link quality estimation.

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Author Contributions

Debraj Basu is the primary author of the paper and has done all the experimental work and analysis to support the various observations. Gourab Sen Gupta, Giovanni Moretti, and Xiang Gui are the research supervisors who have contributed with their ideas and direction to facilitate the research and develop the research paper.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Weiser, M. Ubiquitous Computing. Available online: http://www.ubiq.com/weiser/UbiHome.html (accessed on 17 September 2015).
2. Philips Research—Technologies. What Is Ambient Intelligence? Available online: http://www.research.philips.com/technologies/projects/ami/ (accessed on 17 September 2015).

3. Limitations of Batteries in Powering Wireless Sensors. Available online: http://www.perpetuapower.com/battery_limitations.htm (accessed on 17 September 2015).
4. Perpetual Power Solutions to Save $1 billion in Labor Costs. ONWORLD. Available online: http://onworld.com/html/newsperpower.htm (accessed on 17 September 2015).
5. Sheu, J.P.; Hsieh, K.Y.; Cheng, Y.-K. Distributed Transmission Power Control Algorithm for Wireless Sensor Networks. *J. Inf. Sci. Eng.* **2009**, *25*, 1447–1463.
6. Lin, S.; Zhang, J.; Zhou, G.; Gu, T.H.L.; Stankovic, J.A. ATPC: Adaptive Transmission Power Control for Wireless Sensor Networks. In Proceedings of the 4th International Conference on Embedded Networked Sensor Systems, Boulder, CO, USA, 1–3 November 2006; pp. 223–236.
7. Baccour, N.; Koubaa, A.; Mottola, L.; Zuniga, M.A.; Youssef, H.; Boana, C.A.; Alves, M. Radio Link Quality Estimation in Wireless Sensor Networks: A Survey. *ACM Trans. Sens. Netw.* **2012**, *8*, 1–35.
8. Chipcon products from Texas Instruments. 2.4 GHz IEEE 802.15.4/ZigBee-ready RF Transceiver. Available online: http://www.ti.com/lit/ds/symlink/cc2420.pdf (accessed on 17 September 2015).
9. Fu, Y.; Sha, M.; Hackmann, G.; Lu, C. Practical Control of Transmission Power for Wireless Sensor Networks. In Proceedings of the 20th IEEE International Conference on Network Protocols, Austin, TX, USA, 30 October–2 November 2012; pp. 1–10.
10. Hackmann, G.; Chipara, O.; Lu, C. Robust Topology Control for Indoor Wireless Sensor Networks. In Proceedings of ACM Conference on Embedded Network Sensor Systems, Raleigh, NC, USA, 5 November 2008; pp. 57–70
11. Soltani, S.; Ilyas, M.U.; Radha, H. An Energy Efficient Link Layer Protocol for Power-Constrained Wireless Networks. In Proceedings of International Conference on Computer Communications and Networks (ICCCN), Maui, HI, USA, 31 July 2011; pp. 1–6.
12. Zheng, L.; Wang, W.; Mathewson, A.; O'Flynn, B.; Hayes, M. An Adaptive Transmission Power Control Method for Wireless Sensor Networks. In Proceedings of Signals and Systems Conference (ISSC 2010), Cork, Ireland, 23–24 June 2010; pp. 261–265.
13. Jeong, J.; Culler, D.; Oh, J.-H. Empirical Analysis of Transmission Power Control Algorithms for Wireless Sensor Networks. In Proceedings of International Conference on Networked Sensing Systems, Braunschweig, Germany, 6–8 July 2007; pp. 27–34.
14. Lal, D.; Manjeshwar, A.; Herrmann, F.; Uysal-Biyikoglu, E.; Keshavarzian, A. Measurement and characterization of link quality metrics in energy constrained wireless sensor networks. In Proceedings of Global Telecommunications Conference (GLOBECOM '03), San Francisco, CA, USA, 1–5 December 2003; Volume 1, pp. 446–452.
15. Sheth, A.; Han, R. An Implementation of Transmit Power Control in 802.11b Wireless Networks. University of Colorado at Boulder, Boulder, CO, USA, 2002.
16. Eberspächer, J.; Vögel, H.J.; Bettstetter, C.; Hartmann, C. *GSM—Architecture, Protocols and Services*; Wiley: New York, NY, USA; Chapter 4, 2009.
17. ENERGIZER CR2320. Available online: http://data.energizer.com/PDFs/cr2320.pdf (accessed on 17 September 2015).
18. EB-B600BUBESTA. SAMSUNG. Available online: http://www.samsung.com/us/mobile/cell-phones-accessories/EB-B600BUBESTA (accessed on 17 September 2015).

19. Gsmarena. Available online: http://www.gsmarena.com/apple_iphone_5-4910.php (accessed on 17 September 2015).
20. Vandervell, A. Nokia Lumia 1520: Battery Life and Verdict. Available online: http://www.trustedreviews.com/nokia-lumia-1520-review-battery-life-and-verdict-page-5 (accessed on 17 September 2015).
21. Basu, D.; Gupta, G.S.; Moretti, G.; Gui, X. Protocol for improved energy efficiency in wireless sensor networks to support mobile robots. In Proceedings of International Conference on Automation, Robotics and Applications (ICARA), Queenstown, New Zealand, 17–19 February 2015; pp. 230–237.
22. nRF24L01+ Single Chip 2.4GHz Transceiver Product Specification v1.0. Available online: http://www.nordicsemi.com/eng/Products/2.4GHz-RF/nRF24L01P (accessed on 17 September 2015).
23. CC2500 Low-Cost Low-Power 2.4 GHz RF Transceiver. Available online: http://www.ti.com/lit/ds/symlink/cc2500.pdf (accessed on 17 September 2015).
24. Exponential backoff. Available online: http://en.wikipedia.org/wiki/Exponential_backoff (accessed on 17 September 2015).
25. IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Ph. IEEE Computer Society: Washington, DC, USA, 2002.
26. Schmidt, D.; Berning, M.; Wehn, N. Error correction in single-hop wireless sensor networks—A case study. In Proceedings of Conference & Exhibition of Design, Automation & Test in Europe, Nice, France, 20–24 April 2009; pp. 1530–1591.
27. Rappaport, T. *Wireless Communications—Principles and Practice*; Prentice Hall PTR: Upper Saddle River, NJ, USA, 2002; pp. 177–253.
28. Universal Mobile Telecommunications System (UMTS); Selection procedures for the choice of radio transmission technologies of the UMTS (UMTS 30.03 Version 3.1.0). UMTS: Sophia Antipolis Cedex, France, 2011.