Performance Comparison of A New Non-RSSI Based Wireless Transmission Power Control Protocol with RSSI Based Methods: Experimentation with Real World Data

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Abstract

In this paper, simulations with MATLAB are used to compare the performance of a RSSI-based output power control with non-RSSI based adaptive power in terms of saving energy and extending the lifetime of battery powered wireless sensor nodes. This non-RSSI (received signal strength indicator) based adaptive power control algorithm does not use RSSI side information to estimate the link quality. The non-RSSI based approach has a unique methodology to choose the appropriate power level. It has drop-off algorithm that enables it to come back from a higher to a lower power level when deemed necessary. The performance parameters are compared with the RSSI-based adaptive power control algorithm and fixed power transmission. In order to evaluate the protocols in the real world scenarios, RSSI data from different indoor radio environments are collected. In simulation, these RSSI values are used as an input to the RSSI based power control algorithm to calculate the packet success rates and the energy expenditures. In this paper we present extensive analysis of the simulation results to find out the advantages and limitations of the non-RSSI based adaptive power control algorithm under different channel conditions.

Keywords: wireless sensor network, energy consumption optimization, adaptive power control

1. Introduction

The proliferation of low power wireless sensor networks 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 any-time and any-where. The technology has enormous potential and a wide range of applications such as, environmental monitoring, health monitoring for assisted living (smart home environments) and industrial and plant monitoring (Industrial automation).

1.1 Related work in transmission power control for energy efficiency

Power saving approaches can be broadly classified into media access control (MAC) layer solutions and network layer

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solutions [3]. Network layer solution means that the different transmission parameters can be modified to achieve the set goal. This paper discusses the use of received link quality information (RSSI/LQI) to adjust output transmission power.

1.2 RSSI/LQI based power control algorithms for energy efficiency

The RSSI-based power control approaches is guided by closed loop control between the transmitting node and the receiving base station mechanism. RSSI is a measurement of signal power and which is averaged over 8 symbols of each incoming packet [4]. On the other hand, LQI is usually vendor specific and is measured based on the first eight symbols of the received packet as a score between 50 and 100 [5].The general steps are described below as

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

During initialization 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 of the RSSI and the output power level, the transmitter selects the required power level.

In paper [4], Shan Lin et al. have introduced adaptive transmission power control (ATPC) that maintains a neighbor table at each node and a feedback loop for transmission power control between each pair of nodes. ATPC provided the first dynamic transmission power algorithm for WSN that uses all the available power output levels of CC2420 [6].

Practical-TPC [7] 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 attempt. While ATPC uses all 32 power levels, there are some algorithms that divide these 32 power levels into 8 levels, as in [3]. The work described is this paper aims to avoid the need for such probe packets and their associated energy cost. ART (Adaptive and Robust Topology control) protocol [8] has been designed for complex and dynamic radio environments. It adapts the transmission power in response to variation in link quality or degree of contention. Analysis of the paper has suggested that RSSI and LQI (Link Quality Indicator) may not be good or the most reliable indicators of link quality, especially in robust indoor radio environment.

Paper [3] also has an initialization phase and a maintenance phase while adjusting transmission power. In the initialization phase, each of the sensor nodes uses the 8 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 with 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) [9] protocol uses error correction mechanism to maintain reliable communication. 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 [10], the approach is similar to ATPC where the power-distance table is maintained at each node. The distance is the minimum power of one node with the neighboring node. In multi-hop wireless sensor network, optimization of the transmission power is, therefore, the shortest path problem based on the power-distance relationship. In [11], the authors have proposed a power control algorithm in which each sensor node also uses beacon messages to determine its neighbors and the corresponding minimum transmission power. After the neighbors 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 neighboring nodes. Authors have combined dynamic transmission power control of the link layer protocol with the reduction of duty cycle of MAC layer to save energy.

Paper [12] has 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 average energy consumption as the cost metrics.

The application of an adaptive power control algorithm for IEEE 802.11 in the technical report of [13] aims to modulate the transmit power based on the distance between the communicating nodes to the minimum level such that the destination node still achieves correct reception of a packet despite intervening path loss and fading. It used a radio module with 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.

RSSI/LQI based adaptive power control algorithms are an attractive alternative to save energy. It is to be noted that these algorithms are mainly designed for multi-hop network where each sensor node broadcast beacon packets and discover its neighbor to which it can transmit at minimum power. However, there are two factors that are worth considering. They are

- There is an initial overhead cost for building up the RSSI vs. Power level table.
- In case the sensor is mobile, the refreshing frequency of the table becomes crucial and that also adds up to the cost.
- Even when the sensors are stationary, there is no clear indication in any of the papers ([3-4], [6-13]) as to what would be the ideal channel sampling frequency that would optimise energy efficiency.

Most of the network level power control algorithms that are discussed above use link quality information (RSSI or LQI) for adjusting the output power. The adaptive power control algorithm has a unique channel estimation method without RSSI side information. Therefore, this algorithm is best suited for those radio modules that do not support RSSI values. The nRF24L01p radio transceiver module from Nordic Semiconductor Inc. [14] has configurable four 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 NRF24L01+

Operational mode	Current consumed mA
Transmission @ 0 dBm output power (MIN)	11.3
Transmission @ -6 dBm output power (LOW)	9
Transmission @ -12 dBm output power (HIGH)	7.5
Transmission @ -18 dBm output power (MAX)	7

The transceiver can transmit at four power levels: -18 dBm, -12 dBm, -6 dBm and 0 dBm. In general, a wireless transceiver has different modes of operation.

Among other methods of energy aware data transmission in WSN or mobile application, the work of Zhang et.al has been noteworthy. In [15], the authors have proposed a novel topology control approach for wireless sensor networks (WSNs) where the edge weight and vertex strength take sensor energy, transmission distance, and flow into consideration. Zhang and Liang have proposed a novel method of service aware computing for uncertain mobile applications to ensure QoS for these devices supporting various applications [16]. In industrial applications of WSNs, an energy-balanced routing method based on forward-aware factor (FAF-EBRM) has been proposed by the authors in [17]. In this multi-hop routing algorithm, the next node is selected based on information about the link weight and forward energy density. In [18], authors have designed and implemented a solution of embedded un-interruptible power supply (UPS) system forward for long-distance monitoring and controlling of UPS based on Web. Zhang et.al, have proposed a novel multicast routing method with minimum transmission for WSN of cloud computing service [19].

In [20], Zhang has proposed a fusion decision method to support an attentive mobile learning paradigm. The learning method tracks the users' movement without any active devices. The objective is to achieve seamless mobility for mobile services, especially mobile web-based learning. In the RFID (radio-frequency identification) domain, one of the key issues is the packet losses due to collision when the RFID tags transmit within the collision window (time). In [21], a novel anti-collision approach has been proposed by Zhang et.al. In this method, a mapped correlation of the IDs of the RFID tags is used to increase the association between the tags. In [22], the authors have proposed agent-based proactive migrating method with service discovery and key frames selection strategy. The designed system is convenient to work and use during mobility, and which is useful for mobile user in the big data environments (BDE).

2. Adaptive transmission power control methods: Non-RSSI based and RSSI-based

This section discusses about the novel transmission power control protocol that does not use RSSI data for channel estimation and the RSSI-based power control method.

2.1 Non- RSSI/LQI based channel estimation and power control algorithms for energy efficiency

The non-RSSI based channel estimation and output power control algorithm is proposed in [23-24]. The basis of this lightweight adaptive algorithm is the states where each state represents one cycle of packet transmission. In each state there are output power levels in increasing order which can be used by the transmitter. State transition occurs depending on the power level at which the transmission is successful or failed. State 4 uses only the maximum power level and is allowed to transmit 4 times. There is no direct transition from state 4 to state 1 or 2. Similar conditions hold true when transiting from 3. The most energy efficient state is 1. The more it stays in state 1, the more it saves energy. State 4 is where the maximum energy may be used to transmit the packet. The adaptive algorithm is designed in such a way that it takes into account of performances in each state. It also has a unique drop-off algorithm that allows it to drop down to a lower state when deemed necessary. 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. Fig. 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.

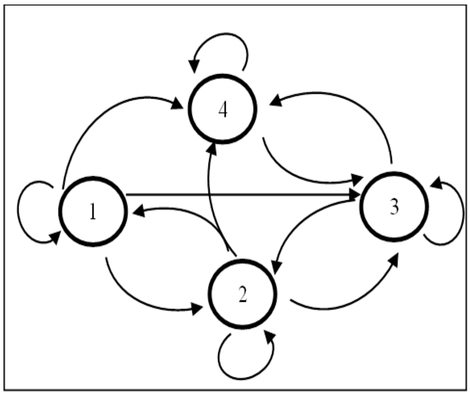

Fig. 1 State transition diagram of the adaptive algorithm

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)	Low (L)		
	High (H)	High (H)	High (H)	
	Maximum (X)	Maximum (X)	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 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

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.

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).

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

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

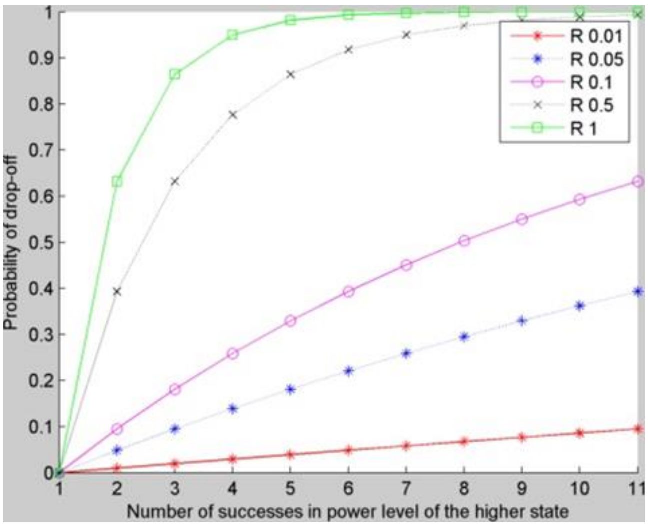

Fig. 2 The curves behave differently depending on the value of R. A low R value indicates slow back off while a high R indicates fast back off. When the number of successes is 0, the probability of transition is 0. This drop-off algorithm takes into account of all the previous successes indicating that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

The plots in Fig. 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 nth retransmission attempt is chosen as a uniformly distributed random integer r in the range $0 < r < 2k$.

where $k = \min(n, 10)$, 10 is the maximum number of retries allowed.

The nth 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 [25-26].

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 this paper, this protocol is compared with the standard RSSI-based channel estimation and power control algorithm (ATPC) using real world RSSI data when sensors are stationary. The next section explains the ATPC protocol in details.

2.2 ATPC: Adaptive Transmission Power Control for wireless sensor networks

The first adaptive power control protocol for wireless sensor network was proposed in [4]. Results show that the ATPC only consumes 53% of the transmission energy of the maximum transmission power solutions and 78.8 % of that of network level transmission power solutions [3]. In ATPC, the sensor nodes build a model for each of its neighboring nodes that describe the correlation between the transmission power and the link quality. The radio link quality varies over time and with environment. The objective of the ATPC protocol is to find out the minimum transmission power level to maintain a good quality link (~PSR > 98%) and dynamically change the transmission power level over time to address the time varying nature of the wireless channel. Each node sends beacon packets at different transmission power level to the neighboring node and makes note of the RSSI value that it receives on the feedback path. Based on this information, the node builds a predictive model and uses least square approximation method to calculate the desired transmission power level.

In run time, it also monitors the link quality by using the information of RSSI and setting the upper and the lower limits to the link quality estimator. As long as the RSSI value is steady and within the range, the transmitter is not required to adjust the power level. Therefore, the upper and lower limits are critical design parameter to make ATPC energy efficient. The other important parameters of ATPC protocol are the link quality threshold, the frequency of transmission power control and the number of sample packets in the setup phase. Based on the empirical findings regarding the temporal variation of the link quality, the paper suggested that one packet per hour would maintain the freshness of the predictive model.

3. Simulation parameters

The general simulation parameters are presented in Table 5.

Table 5 General simulation parameters for comparison of ATPC with non-RSSI based adaptive protocol in MATLAB

Modulation technique	BFSK
Channel data Rate	250 kbps
Maximum Doppler spread	20 Hz
Packet size	41 bytes
Cyclic redundancy check	CRC-16
Multi-path Fading channel model	UMTS Indoor Office Test Environment [27]
E_b/N_0	Derived from the RSSI values
Retry limit in fixed power transmission and ATPC	3
Retry limit to highest power level in state 4 of adaptive protocol	3
RSSI threshold	-90 dBm

3.1 Simulation design of the working principle of ATPC

The ATPC protocol changes its output power based on the RSSI value of the most recent transmitted packet. It has the four power levels to choose from and uses the decision matrix as explained in Table 6. It is known that the minimum RSSI level to maintain high PSR (> 95%) is approximately -90 dBm [28] [5]. Therefore, it is set as the minimum threshold. Here RSSI_TH is the RSSI threshold and RSSI is the received signal strength indicator of the transmitter packet. In this simulation, the performances of the ATPC are observed at channel sampling/scanning interval of 1, 5, 10, 50 and 100 transmissions.

Table 6 Decision matrix table of ATPC on run time

		New transmission power level			
		-18 dBm	-12 dBm	-6 dBm	0 dBm
Current Power level	-18 dBm	RSSI >= RSSI_TH	RSSI_TH - RSSI <= 6 dB	6 dB < RSSI_TH - RSSI < 12 dB	RSSI_TH - RSSI > 18dB
	-12 dBm	RSSI - RSSI_TH >= 6	RSSI - RSSI_TH ~ 0	RSSI_TH - RSSI <=6	RSSI_TH - RSSI > 6
	-6 dBm	RSSI- RSSI_TH >= 12 dB	RSSI- RSSI_TH <=6 dB	RSSI - RSSI_TH ~ 0	RSSI-TH- RSSI > = 6 dB
	0 dBm	RSSI- RSSI_TH >= 18 dB	6 dB < RSSI – RSSI_TH <= 12 dB	RSSI – RSSI_TH <= 6 dB	RSSI - RSSI_TH ~ 0

During each cycle of power control, the ATPC compares the present RSSI with the RSSI_TH. If the difference between the current RSSI and RSSI_TH is negligible or equal to 0, then the new power level is same as the old power level. These conditions are highlighted in bold brown. Only when the current power level is -18 dBm and RSSI is greater than the RSSI_TH, it sticks to -18 dBm.

3.2 Conditions when to ramp up output power:

- When RSSI_TH > RSSI, it is required to ramp up power for subsequent packets.
- When RSSI_TH - RSSI ≤ 6 dB, the output power is incremented by 6 dB. For example, when current output power is -12 dBm, then new power level will be -6 dBm. These conditions are highlighted in bold blue.

- When 6 dB < RSSI_TH - RSSI < 12 dB, then the output power level is incremented by 12 dB. For example, if the current output power is -18 dBm, then new power level will be -6 dBm. These conditions are highlighted in bold black.
- When RSSI_TH - RSSI ≥ 12 dB and the current power level is -18 dBm, then the new power level will be 0 dBm.
- When RSSI_TH - RSSI ≥ 6 dB and the current power level is -12 dBm, then the new power level will be 0 dBm.

3.3 Conditions when to ramp down output power:

- When RSSI - RSSI_TH ≥ 18 dB and output power is 0 dBm, then power level can be decremented by 18 dB to -18 dBm as that will satisfy RSSI ≥ RSSI_TH.
- But when 6 dB < RSSI – RSSI_TH ≤ 12 dB, the output power level decrements to -12 dBm. When RSSI – RSSI_TH ≤ 6 dB, the output power level decrements by 6 dB.
- When RSSI - RSSI_TH ≥ 6 dB and current power level is -12 dBm, then the current power level can be decremented by 6 dB to -18 dBm.
- Finally, when the current power level is -6 dBm and RSSI- RSSI_TH ≤ 6 dB, the power level decrements to -12 dBm, while if RSSI- RSSI_TH ≥ 12 dB, it decrements by 12 dB.

It is known that the minimum RSSI level to maintain high PSR (> 95%) is -90 dBm. Therefore, -90 dBm is set as the minimum threshold. Here RSSI_TH is the RSSI threshold and RSSI is the received signal strength indicator of the transmitter packet. In this simulation, the performances of the ATPC are observed at channel sampling/scanning interval of 1, 5, 10, 50 and 100 transmissions.

4. Performance parameters

The performance parameters are:

- Average cost per successful transmission
- Expected success rate or protocol efficiency [15]

One of the parameters for the optimization is the energy consumed per useful bit transmitted over a wireless link [3, 29]. Similarly in this paper, the cost per successful transmission has been considered.

$$C_{s\_avg} = \frac{C_T}{P_S - P_L} \qquad (1)$$

where

C_{s_avg} = average energy cost per successful transmission

C_T = total cost of transmission

P_L = number of lost packets

P_S = Number of packets to send

All cost values are measured in mJoules. 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 total packet to send count does not include the retry packets. Therefore, the denominator in equation 3 is only 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 [3]. It can also be defined as the expected number of successes per 100 transmissions. Mathematically,

$$Succ_{rate} = \frac{P_S - P_L}{P_S + Ret_T} \qquad (2)$$

where

$Succ_{rate}$ = expected success rate

Ret_T = total number of retries

Here $P_S - P_L$ = total number of successes (P_{succ}). If both the numerator and denominator are divided by Ps, then in percentage term,

$$Succ_{rate}(\%) = \frac{PSR}{1 + Ret_{avg}} \tag{3}$$

where

Ret_{avg} = average number of retries per packet and is defined as

$$Ret_{avg} = \frac{Ret_T}{P_S} \tag{4}$$

Here,

$$PSR = \frac{P_{succ}}{P_S} * 100 \tag{5}$$

This parameter indicates the total number of transmissions (on average) to achieve a given packet success rate (PSR).

5. Collection of the RSSI values

In this paper, we have considered a star topology where all the sensors connect to one base station via a single hop. These sensors are responsible for transmitting, for example, temperature, humidity and occupancy data as well as health related vital information in a smart home environment with assisted living. In industrial set up, these sensors transmit key monitoring parameters like humidity and temperature, valve control position among others. These kind of indoor radio environments pose challenge in terms of reliable data delivery and energy efficiency of the sensor node. This is because the radio signal in indoor environment 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 movement 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. In order to study the variation of the signal level in these kind of indoor radio environment, the RSSI values from the access points of wireless LAN setup in office environment, commercial setup (shopping center) and social setup (University dining hall) are collected.

The primary source of noise or interference to the signal that is considered in this paper is the signal attenuation because of distance, the partitions in between the transmitter and the base station and the momentary signal fluctuation due to multipath fading as well as movements of people in between the sensor and the base station.

The NetSurveyor tool [30] was used to collect RSSI of beacon signals from a wireless access point that are send every 5 seconds. NetSurveyor is an 802.11 (Wi-Fi) network scanning cum discovery tool that gathers information about nearby wireless access points in real time. These beacon frames are transmitted periodically by the WIFI access points (AP) to announce the presence of a wireless LAN [31-32]. It contains all the information about the network. Since the AP transmits at a fixed power level, any variation in the RSSI value is an indication of the link quality variation, therefore, the received E_b/N_0. There were several APs that were transmitting the radio beacon signal. For the simulation purpose, the RSSI data of that AP was used that was providing the strongest signal. The access point emulates the transmitting sensor while the data collection device (the laptop in this case) acts as the base station.

In simulation, these RSSI values correspond to the minimum output power level (-18 dBm). Hence, it indicates the base channel condition over which power ramping may be required to meet the link quality requirement. This link quality change can be transient or have an effect over a longer period of time. Therefore, the RSSI values can be used to adapt or manipulate the output power. This setup emulates the real world approach of ATPC protocol where the RSSI values from the neighboring node in response to the beacon signal are used to setup the output power level in the initialization phase or during run time. In the single hop topology, it is the hub that piggybacks the RSSI information to the sensor. A 5 second interval between fresh RSSI values indicates that the sensor is transmitting at a rate of 1 packet every 5 seconds and therefore has received the RSSI value as the feedback from the hub.

5.1 Data collection scenarios and calculation of the E_b/N_0

There are two types of RSSI variation scenarios that are investigated. They are collected from three different environments after an interval of 5 seconds. They are

- Three sets of long term data over a period of approximately 10 hours from within University campus building. The distance between the transmitter and receiver is approximately 24 meters.
- Three sets of short term data over the busy period of the day (approximately between 90 minutes and 120 minutes) from town shopping centre. The distance between the transmitter and receiver is approximately 30 meters.
- Three set of short term data over the busy period of the day (approximately between 90 minutes and 120 minutes) from University dining hall. The distance between the transmitter and receiver is approximately 25 meters.

5.2 Images of the mentioned scenarios are added in appendix

RSSI is a measurement of signal power and which is averaged over 8 symbols of each incoming packet [4]. The value of RSSI is dependent on the received power, the channel data rate and the noise spectral density (N¬0). If the received average bit energy is denoted by E_b and channel data rate as R, then by definition, in dBm,

$$RSSI = \frac{E_b}{N_0} + Noise\,Power \quad (6)$$

If the noise floor is assumed to be constant, the RSSI value will depend on the average bit energy and channel data rate. In dBm scale, the relationship between the RSSI and E_b/N_0 is linear with intercept of -119.9978 dBm at x-axis. Different data rate will have different intercept values when the noise floor level is kept constant. The value of -119.9978 is derived from the value of N_0 and channel data rate set at 250 kbps for simulation.

$$Noise\,Power = KTR \quad (7)$$

where

K = Boltzmann's constant (1.28 x10-23 Joules/Kelvin)

T = Noise temperature in Kelvin (290 K) and

R = 250 kbps

Therefore, the linear relationship between RSSI and E_b/N_0 takes the following form in equation (9) which is derived from equation (7).

$$RSSI = \frac{E_b}{N_0} - 119.9978 \quad (8)$$

6. Comparison of the optimal cost values of ATPC, adaptive power control and fixed power transmission using RSSIdata from three different locations

In section 6, performance parameters of ATPC, fixed power and non-RSSI based adaptive power control algorithms are compared.

6.1 Long term RSSI data collected over a period of approximately 10 hours inside University building

Two sets of data are collected during the period of approximately 10 hours. The busy hour RSSI variation was captured by logging the data between 8:30 a.m. till 5 p.m. The variation of E_b/N_0 over time for one of the data sets is presented in Fig. 3. The RSSI data are collected using a laptop. Using equation (4), the RSSI values are converted to corresponding E_b/N_0 values. The occasional drop to 20 dB is due to fading. Overall, this indicates that the channel link quality is very good.

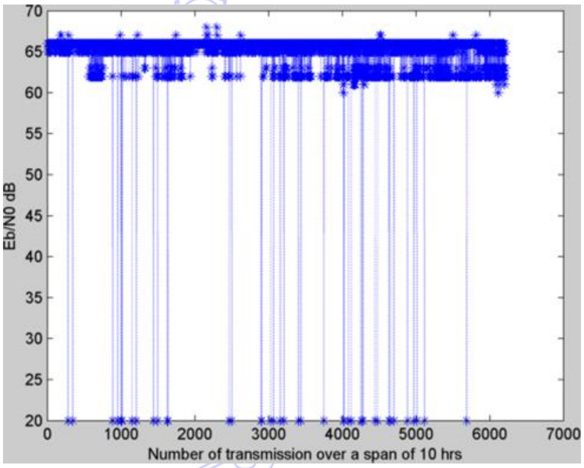

Fig. 3 The variation of the average E_b/N_0 over time. Along x-axis, the numbers of transmissions are noted. The average E_b/N_0 is quite high (>60 dB) and occasionally dropped to 20 dB. Since the distance between the access point and the laptop is constant, the drop in the value is attributed to human movements in between and multipath effects

The normalized frequency distribution plots of the E_b/N_0 of one of the data sets are shown in Fig. 4.

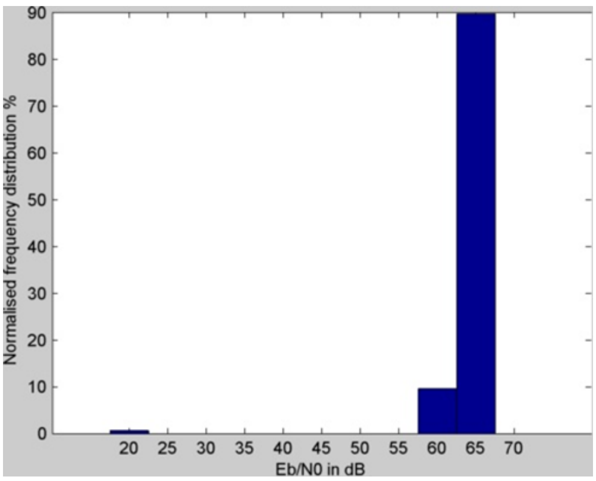

Fig. 4 The frequency distribution plot of the received E_b/N_0 from data set 1 shows that occasionally the signal level has dropped by 30-40 dB, primarily due to multipath fading. Overall, the link quality has been good

The normalized frequency distributions of the other two data sets are also similar to the one shown in Fig. 4. The frequency distribution plots also signify the amount of time (%) the channel link quality has remained above a certain value. In both these figures, a high % of time (>85%) the E_b/N_0 is more than or equal to 60 dB. The PSR and the efficiency values of all the transmission strategies are 100 and higher that 98% respectively and their differences are negligible. Therefore, they are not plotted. Table 7 shows the average values of the performance parameters of the different transmission strategies that are compared in this paper.

Table 7 Average cost, PSR and protocol efficiency of data sets inside University building

ATPC- RSSI based adaptive power control			
Channel scanning frequency	**PSR %**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
Every time the sensor transmits	100	0.0308	99.10
Every 5 transmissions	100	0.0308	99.08
Every 10 transmissions	100	0.0308	99.07
Every 50 transmissions	100	0.0309	99.08
Every 100 transmissions	100	0.0310	99.15
Non-RSSI based adaptive power control			
Drop-off factor R	**PSR %**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
0.01	100	0.0322	98.99
0.05	100	0.0317	98.70
0.1	100	0.0315	98.63
0.5	100	0.0312	98.68
1	100	0.0312	98.57
Fixed power transmission			
Output power	**PSR %**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
-18 dBm	100	0.0306	99.27
-12 dBm	100	0.0326	99.94
-6 dBm	100	0.0390	100.00
0 dBm	100	0.0490	100.00

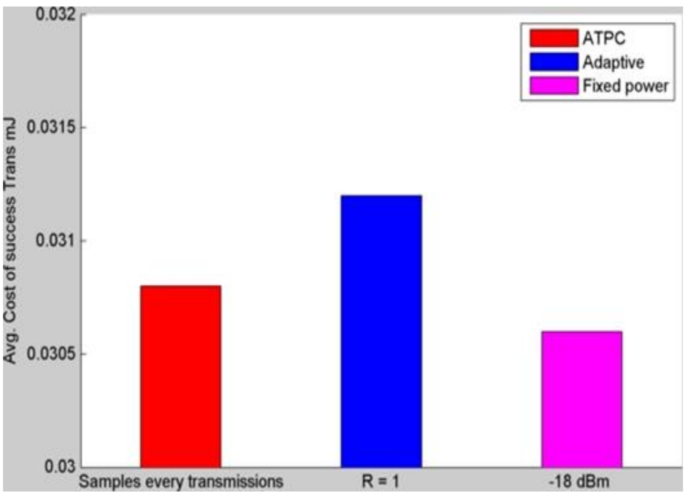

Fig. 5 University building- Comparison of the minimum cost due to different transmission strategy shows that there is hardly any difference in the average cost per successful transmission

Fig. 5 has compared the minimum average cost of successful transmission based on the three data sets of University building.

The optimal cost values of each transmission strategy are plotted. The average E_b/N_0 values due to transmission at lowest power level (-18 dBm) is high. That explains the facts from Fig. 5 that fixed power transmission at -18 dBm provides the most energy efficient solution. Any ramping-up in power level will always be wastage of power. The energy consumption values of the adaptive algorithm matches closely when the value of drop-off rate is 0.5. It signifies that the state-based system can perform most energy efficiently under very good link quality when it drops-off the fastest. Section 6.2 compares the energy cost due to ATPC, adaptive power control and fixed power transmission when the RSSI data are collected over a short and busy period of the day.

6.2 Short term busy hour RSSI data collected from University dining hall during busy hours

The variation of the E_b/N_0 and their normalized cumulative distribution are plotted in Fig. 6 and Fig. 7. The channel link quality is still good, with occasional drop to 20 dB due to multi-path fading effect. Since the over-all link quality is still very good (average E_b/N_0 > 55 dB), the PSR and the efficiency values in all these cases are 100 and higher than 98% respectively and their differences are negligible. Therefore, they are not plotted. The tabulated data of the performance parameters averaged over the three sets of observations are presented in table 8. Fig. 8 compares the minimum cost per successful transmission when University dining hall data are used. The difference in the cost is negligible. This is due to the very good quality of link quality (average E_b/N_0 >55 dB) for most of the time (> 93%).

Table 8 Average cost, PSR and protocol efficiency inside University dining hall

ATPC- RSSI based adaptive power control			
Channel scanning frequency	**PSR %**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
Every time the sensor transmits	100	0.0319	98.65
Every 5 transmissions	100	0.0317	98.21
Every 10 transmissions	100	0.0317	98.14
Every 50 transmissions	100	0.0313	98.05
Every 100 transmissions	100	0.0314	97.86
Non-RSSI based adaptive power control			
Drop-off factor R	**PSR %**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
0.01	100	0.0328	98.19
0.05	100	0.0319	98.21
0.1	100	0.0316	98.15
0.5	100	0.0315	97.98
1	100	0.0314	97.85
Fixed power transmission			
Output power	**PSR %**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
-18 dBm	100	0.0310	97.74
-12 dBm	100	0.0328	99.17
-6 dBm	100	0.0391	99.59
0 dBm	100	0.0490	99.82

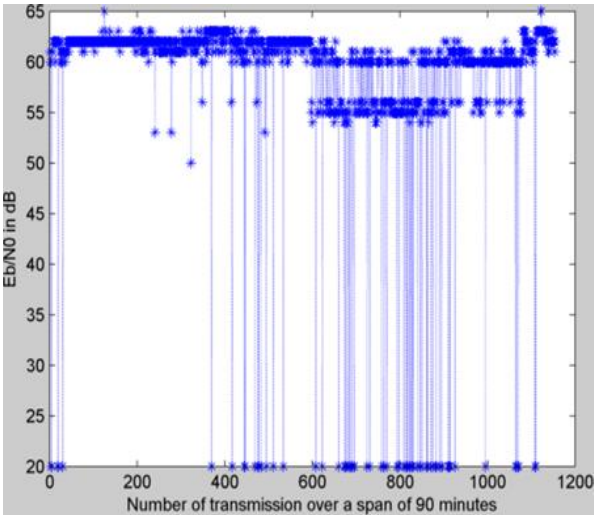

Fig. 6 The variation of the average E_b/N_0 from University dining hall during busy hour between 11:30 a.m. and 1:00 p.m. The average E_b/N_0 is quite high (>55 dB) and occasionally dropped to 20 dB. The busy hour period shows that the average E_b/N_0 can widely fluctuate between high E_b/N_0 (> 55 dB) and low E_b/N_0 (~20 dB)

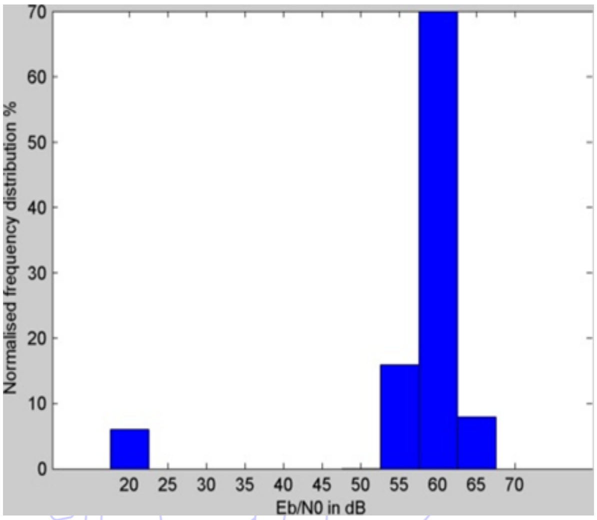

Fig. 7 The frequency distribution plot of the received E_b/N_0 from University dining hall during busy hour shows the rapid fluctuation in the signal level caused by movements of people in between the transmitting sensor and receiver

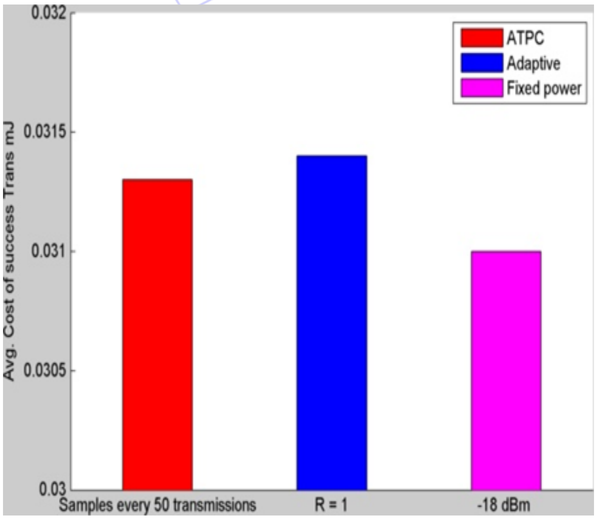

Fig. 8 University dining hall-Comparison of the minimum cost due to different transmission strategy shows that there is negligible difference in the cost per successful transmission

6.3 Short term RSSI data collected from town shopping center during busy hours of weekends

Three sets of short time data during busy hours of the town shopping center have been collected. The nature and the distribution of the variation of the E_b/N_0 values of the two data sets are almost similar. Therefore, the results of one of the sets are only presented. The variation of the E_b/N_0 is plotted in Fig. 9. It shows the significant variation of link quality during busy hours, primarily due to multipath fading effect as people move around in the shopping center.

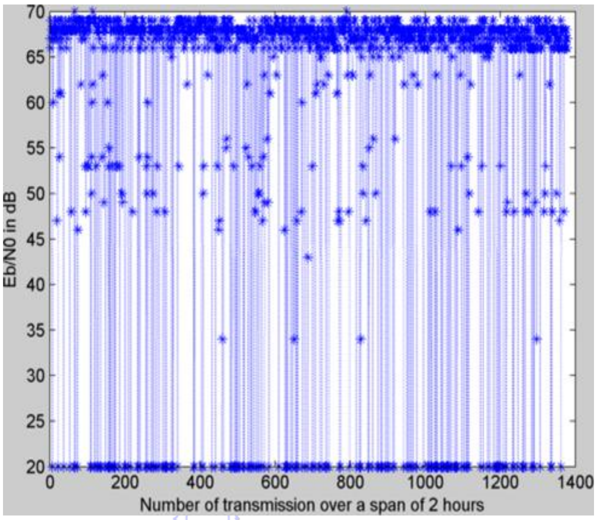

Fig. 9 It shows the variation of the average E_b/N_0 from town shopping center during busy hours between 11:30 a.m. and 1:30 p.m.

The distributions of the E_b/N_0 of the three sets of data are similar in nature. Fig. 1 shows the normalized distribution plot. It is expected that in a town shopping center during busy hours, the signal level will drop more frequently.

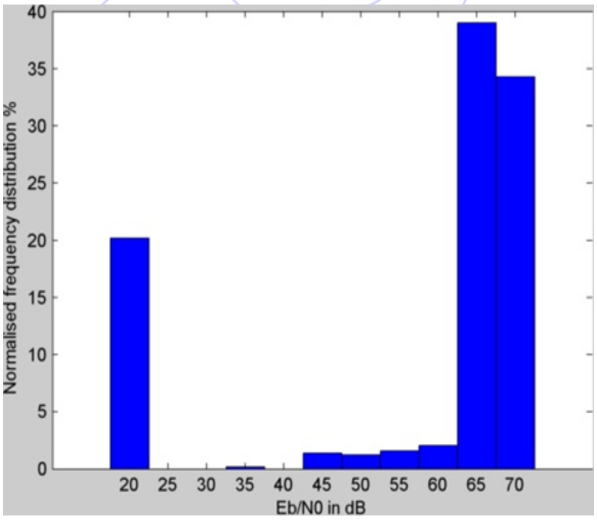

Fig. 10 The distribution plot of the received E_b/N_0 from town shopping centre during busy hours between 11:30 a.m. and 1:30 p.m. shows that E_b/N_0 at 20 dB is significantly high (~20%) which indicates that link quality has fluctuated frequently

Table 9 presents the average values the performance parameters based on the three sets of collected data.

Table 9 Average cost, PSR and protocol efficiency inside shopping centre

ATPC- RSSI based adaptive power control			
Channel scanning frequency	**Avg. Cost per successful transmission mJ**	**PSR %**	**Protocol Efficiency %**
Every time the sensor transmits	0.0315	100	98.44
Every 5 transmissions	0.0314	100	98.03
Every 10 transmissions	0.0314	100	98.02
Every 50 transmissions	0.0313	100	98.12
Every 100 transmissions	0.0311	100	97.88
Non-RSSI based adaptive power control			
Drop-off factor R	**Avg. Cost per successful transmission mJ**	**PSR %**	**Protocol Efficiency %**
0.01	0.0328	100	98.19
0.05	0.0319	100	98.11
0.1	0.0316	100	98.12
0.5	0.0300	100	97.90
1	0.0301	100	97.74
Fixed power transmission			
Output power	**Avg. Cost per successful transmission mJ**	**PSR %**	**Protocol Efficiency %**
-18 dBm	0.0310	100	97.91
-12 dBm	0.0327	100	99.24
-6 dBm	0.0391	100	99.67
0 dBm	0.0490	100	99.82

Fig. 11 compares the cost per successful transmission in different transmission strategies. There is no significant difference observed. The average E_b/N_0 is around 58 dB indicating a fairly good link quality.

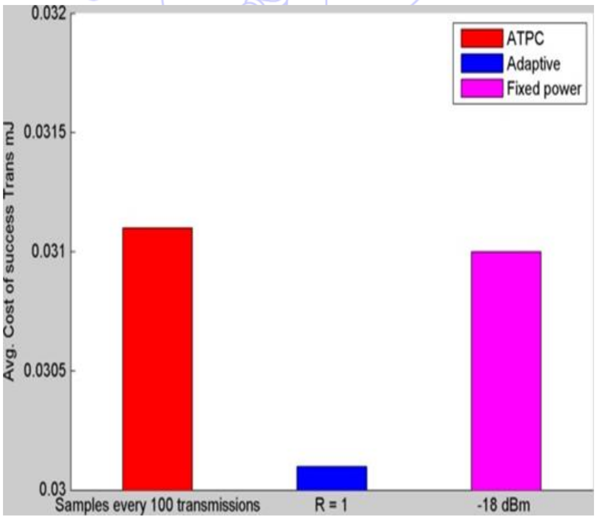

Fig. 11 Town shopping center- Comparison of the minimum cost due to different transmission strategy shows that there is no significant difference in the cost per successful transmission

It can be seen that when the average E_b/N_0 is high (> 55 dB), then even momentary fluctuations in the order of 35-40 dB caused by movements in between the transmitter and the receiver does not seriously affect the packet success rate, the cost of successful transmission and efficiency. In general, the adaptive power control algorithm can be energy efficient as compared to fixed power transmission when there is enough scope or space for manipulation. The results of these section show that when the link quality is good even at -18 dBm output power level, the adaptive algorithm has little scope to save energy. Transmission at the lowest power level provides the minimal solution. In section 7, the mean E_b/N_0 is decremented by 20 dB in order to compare the costs and efficiencies in different transmission strategies.

7. Comparison of PSRs, costs and efficiencies when mean E_b/N_0 is reduced by 20 dB

This section has studied the performance of the transmission strategies when the average or mean E_b/N_0 is reduced by 20 dB. It signifies the scenario when the distance between the sensor and the base station is further increases so that the net path loss is increased. With respect to each of the cases discussed in the previous section, the fluctuation of the E_b/N_0 is now roughly between 0 dB and 40 dB. The adaptive power control protocol (both RSSI and non-RSSI based) are now in a position to modulate the output power level when the signal level has dropped. Results in the next subsection shows that the optimal energy level in fixed power mode is no longer -18 dBm. This higher power level has also pushed the average cost of successful transmission high.

7.1 University building (set 1 and set 2) with average E_b/N_0 reduced by 20 dB

Table 10 shows the average of the performance parameters of the data that were collected. Fig. 12 compares the minimum or the optimal cost of each of the transmission strategies when University building data sets 1, 2 and 3 are used, along with their corresponding PSR and protocol efficiency values. It shows that the non-RSSI based adaptive protocol has proven to be more energy efficient than the fixed power transmission and ATPC. Fig. 12 suggests that the adaptive protocol can save approximately 7% energy as compared to ATPC and can consume 12% less energy than fixed power transmission. The PSR and the protocol efficiency of the non-RSSI based protocol are higher than that of the other two transmission strategies.

Table 10 Average cost, PSR and protocol efficiency inside University building

ATPC- RSSI based adaptive power control			
Channel scanning frequency	**PSR**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
Every time the sensor transmits	95.68	0.0394	88.10
Every 5 transmissions	95.71	0.0400	88.27
Every 10 transmissions	95.87	0.0396	88.52
Every 50 transmissions	95.85	0.0402	88.51
Every 100 transmissions	94.96	0.0404	86.54
Non-RSSI based adaptive power control			
Drop-off factor R	**PSR**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
0.01	99.70	0.0376	94.56
0.05	99.70	0.0370	92.28
0.1	99.70	0.0369	91.16
0.5	99.70	0.0371	88.65
1	99.70	0.0372	87.91
Fixed power transmission			
Output power	**PSR**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
-18 dBm	93.52	0.0413	82.35
-12 dBm	94.69	0.0414	84.03
-6 dBm	99.41	0.0419	94.04
0 dBm	99.99	0.0498	98.67

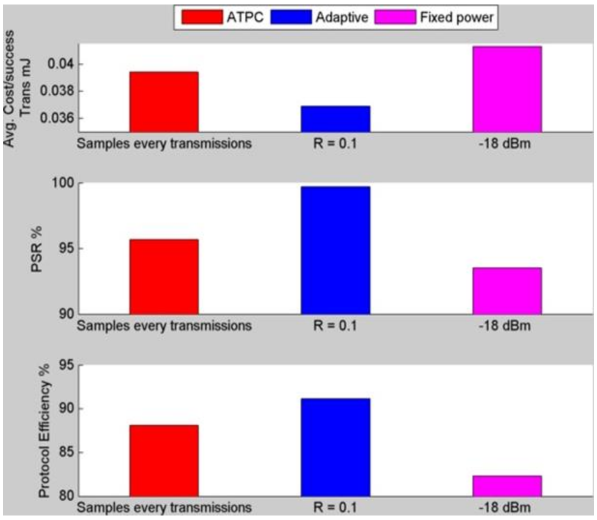

Fig. 12 University building - Comparison of the minimum cost and the corresponding PSR and protocol efficiencies due to different transmission strategy shows that the adaptive protocol can save 7% and 12% energy as compared to ATPC and fixed power transmission and outperforming the others in terms of PSR and efficiency

7.2 *University dining hall with average E_b/N_0 reduced by 20 dB*

Table 11 has tabulated all the performance parameter values of the data that were collected from University dining hall during busy hours.

Table 11 Average cost, PSR and protocol efficiency inside University dining hall during busy hour

ATPC- RSSI based adaptive power control			
Channel scanning frequency	**PSR%**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
Every time the sensor transmits	92.44	0.0461	74.07
Every 5 transmissions	90.43	0.0514	70.45
Every 10 transmissions	89.88	0.0523	69.61
Every 50 transmissions	89.27	0.0534	68.38
Every 100 transmissions	86.62	0.0538	63.33
Non-RSSI based adaptive power control			
Drop-off factor R	**PSR%**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
0.01	99.53	0.0448	92.20
0.05	99.37	0.0431	89.03
0.1	99.16	0.0431	87.22
0.5	98.98	0.0420	84.25
1	98.97	0.0422	83.04
Fixed power transmission			
Output power	**PSR%**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
-18 dBm	83.84	0.0568	60.59
-12 dBm	86.98	0.0556	63.56
-6 dBm	98.46	0.0462	85.42
0 dBm	99.88	0.0508	96.34

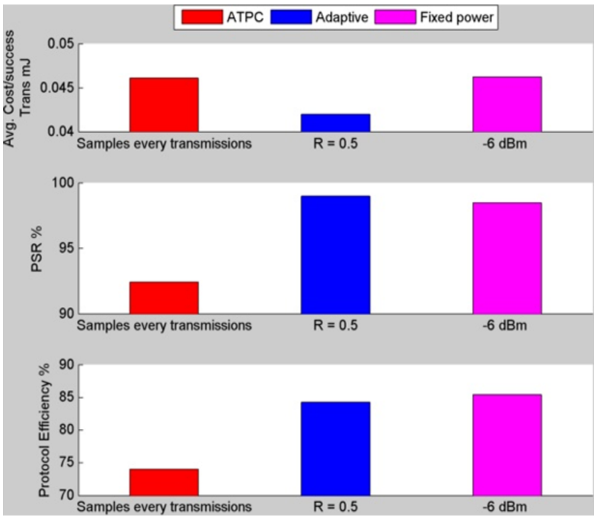

Fig. 13 University dining hall- Comparison of the minimum cost and their corresponding PSR and protocol efficiencies due to different transmission strategy shows that the adaptive protocol consumes 10% less energy than ATPC protocol and fixed power transmission, with comparable PSR and efficiency.

Results of the simulation are shown in Fig. 13. It suggests that the adaptive protocol has emerged out to be the best performer in terms of saving energy. It consumes approximately 10% less energy per successful transmission than ATPC and fixed power transmission.

7.3 *Town shopping center with average E_b/N_0 reduced by 20 dB*

Table 12 has tabulated all the performance parameter values of the data that were collected from University dining hall during busy hours.

Table 12 Average cost, PSR and protocol efficiency inside shopping centre during busy hour

ATPC- RSSI based adaptive power control			
Channel scanning frequency	**PSR %**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
Every time the sensor transmits	90.78	0.0479	70.73
Every 5 transmissions	90.05	0.0498	68.11
Every 10 transmissions	89.37	0.0508	65.62
Every 50 transmissions	88.9	0.0504	65.93
Every 100 transmissions	88.92	0.0522	62.25
Non-RSSI based adaptive power control			
Drop-off factor R	**PSR %**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
0.01	99.83	0.0438	92.20
0.05	99.83	0.0419	89.03
0.1	99.8	0.0417	87.22
0.5	99.85	0.0409	84.25
1	99.83	0.0410	83.04
Fixed power transmission			
Output power	**PSR %**	**Avg. Cost per successful transmission mJ**	**Protocol Efficiency %**
-18 dBm	83.84	0.0568	60.59
-12 dBm	86.98	0.0556	63.56
-6 dBm	98.46	0.0462	85.42
0 dBm	99.88	0.0508	96.34

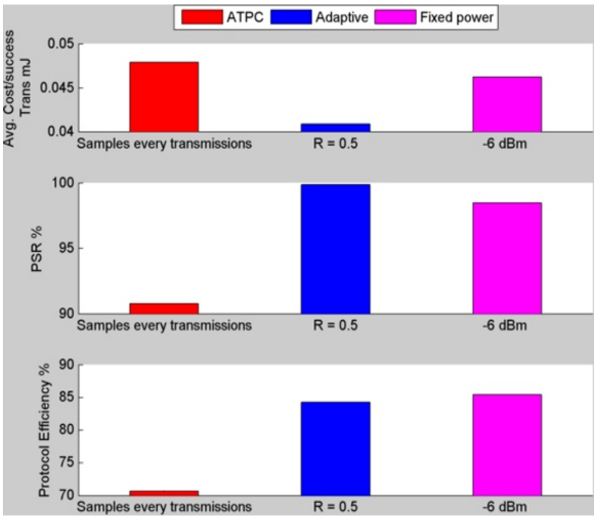

Fig. 14 Town shopping center- Comparison of the minimum cost and their corresponding PSR and protocol efficiencies due to different transmission strategy shows that the adaptive protocol consumes 17% less energy than the ATPC protocol, outperforming the others in terms of PSR and efficiency

Fig. 14 shows that the adaptive protocol has outperformed the ATPC protocol in terms of PSR, protocol efficiency and cost. Referring to Fig. 10, there was enough scope of output power modulation. The occupancy of the link quality around 20 dB (in terms of E_b/N_0) is high (more than 20%). The adaptive protocol makes full use of its adaptive power capability to save energy while maintain a high PSR and protocol efficiency. It is able to save more than 17% energy than ATPC and fixed power transmission.

8. Comparison of PSRs, costs and efficiencies when mean E_b/N_0 is further reduced by 20 dB

If the mean E_b/N_0 is further reduced by 20 dB, then the behavior of the channel is such that it oscillates between a good channel state (E_b/N_0 > 20 dB) and a bad channel state (E_b/N_0 ~ 0 dB). The sample normalized frequency distributions of the E_b/N_0 are shown in Fig.15.

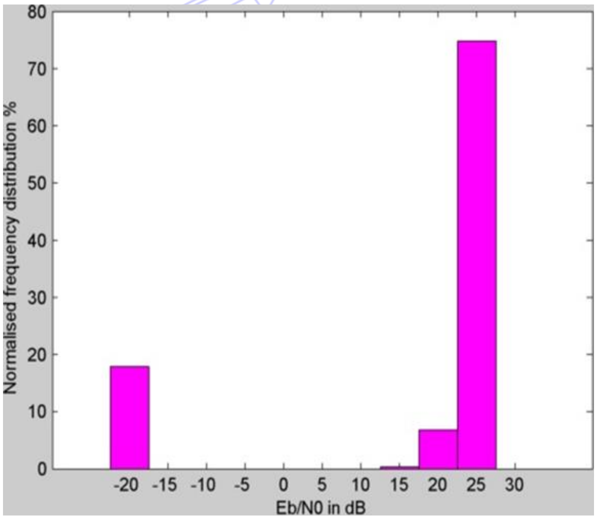

Fig. 15 University building- The normalized frequency distribution of the E_b/N_0 values suggests that channel is in bad condition for ~20% of time.

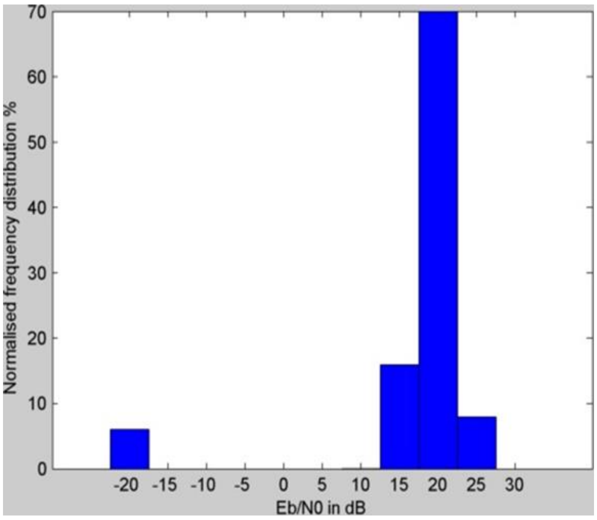

Fig. 16 University dining hall - The frequency distribution of the E_b/N_0 values in during busy hour shows that the channel quality has oscillated between good and bad. In good state most of the packets will be successfully transmitted, while in bad state almost no packet transmission will be successful

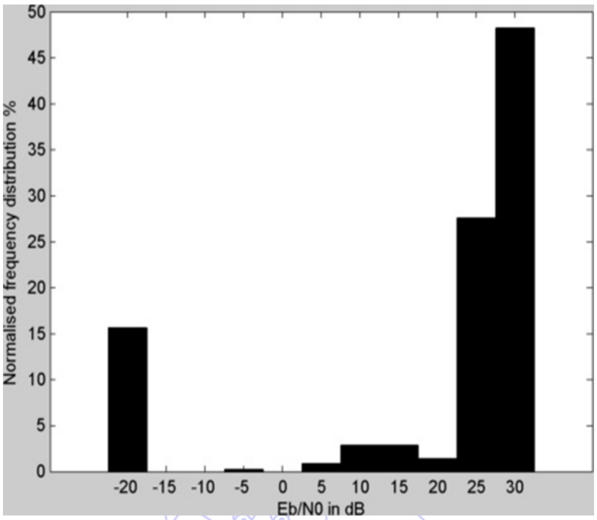

Fig. 17 Town shopping center- The frequency distribution of the E_b/N_0 values during busy hour shows that the channel quality has oscillated between good and bad. In good state most of the packets will be successfully transmitted, while in bad state almost

In such link conditions, the PSR will depend on the occupancy rate of the channel state at or below E_b/N_0 of -20 dB. This is because when the E_b/N_0 is -20 dB, power ramping up to 18 dB is not sufficient to make successful packet transmission possible. All the transmission strategies have approximately similar PSR and protocol efficiency. The fixed power transmission provides the optimal solution in terms of energy required per successful transmission in most of the scenarios that are discussed.

9. Conclusions

The results in this paper demonstrate the advantages and limitations of using power control under different channel conditions to achieve energy efficiency. When the link quality is good (mean E_b/N_0 > 55 dB for the lowest power level) with occasional drop by 20-30 dB due to fading, all the transmission strategies have comparable performances. This is because there was no scope of output power maneuvering to achieve energy efficiency. When the mean E_b/N_0 is dropped by 20 dB, the adaptive power control approach has proved to be energy-saving as compared to fixed power and ATPC when. Under this new channel condition, the mean E_b/N_0 is now approximately 30-35 dB and occasional signal drop to 0 dB has resulted in manipulation of power level. When the mean E_b/N_0 is further dropped by 20 dB, it represented a pure two state channel. The channel link quality oscillates between the good state and the bad state. In the good state, the average E_b/N_0 is around 15-20 dB and most of the packets were successfully transmitted. In the bad state, the average E_b/N_0 is -20 dB and all the packets were dropped. In this type of channel condition, the energy saving solution is provided by the fixed power transmission strategy because any ramping up of output power in bad state will not be sufficient to send a packet successfully. While in good state, it is not required to ramp up power for successful transmission. The non-RSSI approach can be a cost effective solution as compared to a RSSI based channel estimation method (ATPC) when the sensor and the hub are within the communicable distance.

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Appendix A. **Some experimental scenarios and radio propagation environments**

A.1 Within University building

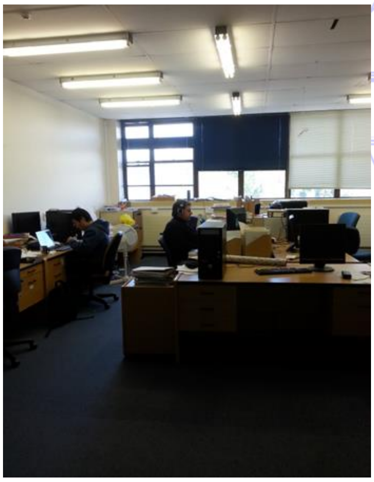

Fig A.1.1 Sample radio environment

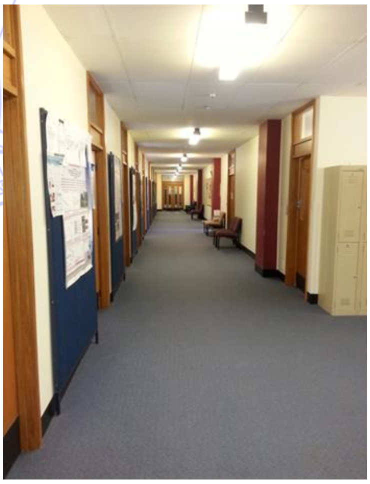

Fig A.1.2 Sample radio environment

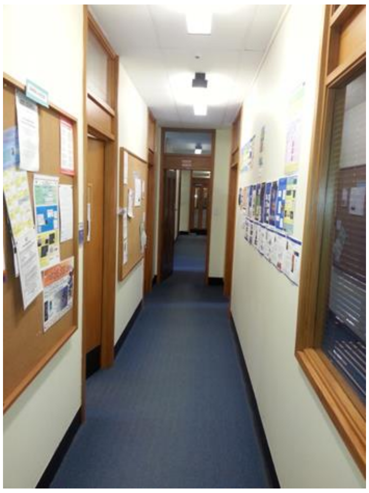

Fig A.1.3 Sample radio environment

A.2 Shopping Mall food court during busy hours

Fig A.2.1 Sample radio environment of Shopping Mall food court

A.3 University dining hall during busy hours

Fig A.3.1 Sample radio environment of University dining hall during busy hours