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Energy Efficiency Comparison of a State Based Adaptive Transmission Protocol with Fixed Power Transmission for Mobile Wireless Sensors

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Abstract

In this paper a state-based adaptive power control protocol (SAPC) has been compared with classical fixed power communication for mobile wireless sensors. The distance between the transmitter and the base station is often not fixed as in the case of body wearable sensors. There can also be unaccounted obstructions in between the transmitter and the receiver. Since signal level attenuates with distance, it is important to choose the right power level that will not only deliver the packets with minimum error but conserve energy at the same time. The proposed adaptive algorithm does not transmit beacon or probe packet for channel quality estimation using the received signal strength before transmitting actual packets. It uses the present and past history of the outcome of packet transmission to evaluate and track link quality. The unique SAPC algorithm also controls the number of re-transmissions in each state. Experimental validation has been done using nRF24L01p transceiver modules. This algorithm can adapt itself to an unknown and variable radio channel in an energy-efficient manner. Experiments were conducted in indoor office environment within a university building and results show that SAPC uses up to 30% less energy than the fixed power communication.

Keywords: Energy efficiency; Mobile sensors; Adaptive power control; Indoor radio

Introduction

The ever increasing application of low power wireless sensor networks has introduced a new research paradigm in energy efficient data transmission methods and collection of target parameters in both indoor and outdoor environments. This can be referred to as pervasive, ubiquitous computing or ambient intelligence [1,2]. Increasingly, there will be a pervasive presence of sensor devices capable of exchanging information with a gateway and perform an assigned task. The sensors, along with the computational and the communication units, and the hub form the ubiquitous sensor network (USN). This technology has diverse application areas, such as environmental monitoring, health monitoring for assisted living (smart home environments) and industrial automation.

The research reported here considers single hop network where the sensors directly communicate with the base station. The sensors are battery powered and therefore are energy constraint. These sensors may be static or mounted on mobile robots or worn by patients to monitor vital health parameters like heart rate, blood pressure, blood sugar level etc.

The primary sources of battery drainage in a sensor module are the following three main operations:

- Sensing
- Computation (involving the microcontroller)
- Communication: Transmitting and receiving

Data comparing energy consumption during computation and trans-receiving suggest that communication is a considerably more expensive undertaking than computation [3]. Therefore, in order to extend the battery lifetime of sensors, they must avoid expensive retransmissions. Battery life impacts the operation cost and performance in terms of wasted energy, expensive battery replacement programs, battery recycling and proper disposal. Therefore, only energy consumption during transmitting and receiving data has been considered for calculating energy efficiency.

Applicability of Mobile Robots in Industry and Healthcare

Mobile robots play a pivotal role in making information available anytime and anywhere. This is because robots can be used for applications that are delicate, heavy, and repetitive or labour intensive [1]. They can be used in assembly lines, in moving stacks of containers in warehouses, asset tracking, cleaning industrial floors etc. The process control and monitoring data such as pressure, humidity, temperature, flow, level, viscosity, and density and vibration intensity measurements are collected through sensing units and transmitted to a control system for operation and management [2]. Wireless sensor equipped mobile robots can also help in reducing the "blind spots" by their ability to collect measurement values on rotating or moving equipment and in remote locations [4].

Tomioka Katsumi et al. have shown the applicability of ubiquitous wireless sensor networks especially in certain monitoring systems [5]. This paper has listed application areas where mobile robots can be used advantageously. Some of the application areas are:

- Facility status monitoring
- Temperature and humidity monitoring systems for warehouses
- Quality control for manufacturing and inspection processes

Figures 1-3 show the placement of sensors and their communication

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Figure 1: Facility status monitoring.





with a server for further data processing. The key challenges in these scenarios are easy access and regular maintenance of sensors. To avoid human intervention and errors, a mobile robot can be used to perform the task of replacement of equipment, batteries for sensors etc.

Traditionally, in healthcare human intervention is required to transport medical equipment, samples, and meals for patients, getting rid of medical waste etc. Mobile robots can eliminate the need for manual transport of laboratory specimens, medications, supplies and other materials, allowing healthcare technicians to focus on patient-related tasks [3,6].

Body sensor networks are a key technology to use different sensor data from patients and help in long term health monitoring. This technology is also used to prevent the occurrence of myocardial infarction, monitoring episodic events or any abnormal condition [7]. These sensors are constantly in touch with the wireless gateway or the access point. Most of these sensors are non-invasive and therefore a patient is allowed to move in freely within the campus facility. Therefore, the distance between the transmitting nodes and the access point also changes constantly. Power control can reduce the energy consumption and increase the lifetime of the body wearable sensors.

These are a few of the possible scenarios where power control can

facilitate energy saving and therefore extend the lifetime of sensor nodes.

Related Work in Transmission Power Control for Energy Efficiency

Strategies related to energy conservation can be broadly classified into media access control (MAC) layer solutions and network layer solutions [8]. This paper has proposed a network layer solution and will discuss some of the existing solutions. Network layer solution means that the different transmission parameters can be modified to achieve the set goal.

Network layer solution

There are several transmission parameters that can be varied to suite the requirement of the application:

- Power
- Modulation technique
- Data rate
- Error correction coding
- Retransmission number control if using ARQ protocol.

However, transceivers use the most energy during transmission [3]; so this paper focuses on adjusting transmission power to reduce the packet error rates, thereby minimizing the number of retries and extending the battery lifetime.

Marabissi et al. present a power and retransmission control policy for use over a fading channel [9]. The approach is not suitable for radios that can only switch between discrete transmit power levels as is typical in current sensors. Farrokh et al. utilized retransmission in a short range wireless network to reduce power consumption, but the use of AWGN (additive white Gaussian noise) channel is very simplistic [10]. The use of Hybrid ARQ (HARQ) protocol in LTE (Long Term Evolution) has gained momentum in the past few years, with the general approach of dynamically adapting the coding rates for failed packet transmission to reduce packet losses. An energy-efficient link layer protocol has been proposed that primarily targets delay sensitive applications such as real-time video communication [11]. Unfortunately, there is a significant overhead in both data transmission and computational costs due to decoding.

In a RSSI or a LQI-based power control approach, the general steps that are followed are:

- The transmitter sends packet at an updated power level to the receiver
- Receiver extract the RSSI value
- If the RSSI is below the given threshold the receiver sends control packet with an updated power level
- At the transmitter, the control packet is received and the current power level is updated for packet delivery [12,13].

In the calibration phase the transmitter sends fixed number of packets at all its available power levels. In the feedback path it receives the RSSI values for each power levels. Based on the relationship between the power levels and the RSSI, the transmitter selects the required power level.

Shan Lin et al. have introduced adaptive transmission power control (ATPC) that maintains a neighbour table at each node and a

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feedback loop for transmission power control between each pair of nodes [12].

Practical-TPC is a receiver oriented protocol that used the packet reception rate (PRR) values to evaluate link quality and determine the output power level [13].

In most of the adaptive power control algorithms for wireless sensors, the nodes exchange probe packets to build the model that relates packet reception ratio with LQI or RSSI. ATPC uses all 32 power levels that are available in the CC2420 transceiver module [12]. There are some algorithms that divide these 32 power levels into 8 levels, as in ref. [8].

REAL (reliable energy adept link-layer) protocol uses error correction mechanism to maintain reliable communication [14]. REAL also uses RSSI/LQI as the channel side information to evaluate radio link quality.

In ref. [15], a power-distance table is maintained at each node. The distance is the minimum power of one node with the neighbouring node. In a mesh network the optimization of the transmission power is the shortest path problem based on the power-distance relationship. This algorithm also depends on the feedback loop to determine the minimum transmission power required for each neighbouring node.

In residential health monitoring, in-hospital patient monitoring and sports monitoring scenarios, sensor are mobile. Paper [16] has provided an empirical analysis of the impact of power control for this kind of mobile sensor network.

In ref. [17], the authors have proposed a power control algorithm that uses beacon messages to discover its neighbours and set the transmission power. Authors have combined dynamic power control with the reduction of duty cycle of MAC layer to save energy. It also investigates the efficacy of duty cycling the nodes rather than put them in idle listening mode when not transmitting.

Paper [18] has introduced the term "link inefficiency" to describe the link quality metrics of energy constrained wireless sensor nodes. In this paper, the cost metrics is calculated to be the time average of the energy consumption.

An adaptive power control algorithm for IEEE 802.11 has been proposed in the technical report of ref. [19]. The objective is to modulate the transmit power based on the distance between the communicating nodes to the minimum level so that the destination node still receive packets overcoming intervening path loss and fading. In the experiments, Cisco Aironet 350 series radio was used that has discrete and configurable output power levels ranging between 0 and 20 dBm. Once the transmitter sends a packet to the receiver, it calculates the optimal transmit power for the new transmission based on the path loss and average RSSI values.

It is to be noted that the power control strategies that are discussed so far are mainly designed for multi-hop network. In a multi-hop scenario, each sensor node broadcast beacon packets and discover its neighbour. Two factors that are worth considering are:

- There is initial energy drainage while building up the RSSI vs. Power level table.
- For mobile sensors, the update rate of the table is crucial.
- Even when the sensors are stationary, there is no clear indication in literature about the optimal update rate to maximise the battery life.

In cellular networks, a power control algorithm is employed to achieve desired signal strength for reliable communication between the mobile station (MS) and the base transceiver station (BTS). Power control is used to reduce co-sector interference and improves over all cell capacity. During an active call, the MS measures the channel's RF link quality after every 480 milliseconds [20]. This helps to maintain a stable link quality which can also improve the battery lifetime of the mobile device. Batteries that power sensor nodes have capacity in the order of 250-300 mAh [21] while those supports mobile devices run in the order of ~1500-3500 mAh [22,23]. Therefore, it is quite likely that a high feedback rate cannot support energy efficient wireless sensor network.

Authors in ref. [24] have proposed the use of retransmissions to reduce energy consumption. It has suggested half power scheme for transmission where the transmission power is reduced to half and allowed to retransmit once. In essence, the transmitter is consuming the same amount of energy. But when it is allowed to retransmit twice at the half power, essentially the packet error rate (PER) is reduced. Reduction in the PER minimises the retransmission probability and therefore the energy consumption. The issue of delay due to retransmission is also considered. The dynamic power control algorithm that is proposed in this paper has set the retransmission limit to 1. If a packet transmission is not successful even after the retry limit, it doubles the power and transmits the same frame again. In case there is an acknowledgement, the signal powered is lowered gradually to save energy.

Most of the power control algorithms that are discussed so far use link quality information (RSSI or LQI) to calibrate the output power. SAPC uses intelligent algorithm to transmit in an energy efficient manner [25-27]. It does not require RSSI to assess condition. This paper has compared the performance of SAPC with fixed power transmission when the transmitting sensor is mobile.

Description of the Adaptive Algorithm

SAPC is a state based adaptive power control algorithm. In each state, the power levels are configured in increasing order of magnitude.

Table 1 shows the power levels based in these states. In the experiments that follow the simulation, nRF24L01p radio modules have been used. This radio module has 4 programmable output power levels. They are 0 dBm, -6 dBm, -12 dBm and -18 dBm. The state transition model can be extended to any number of states, depending on the available power levels of the particular radio module. As the number of states grows, the algorithm can prove to be computationally expensive. It is there advisable to choose power levels with difference of approximately 5 dB in between them.

Figure 4 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.

Hardware Description

For the experiments, nRF24L01+ from Nordic semiconductor

.State	1	2	3	4
Available power	Minimum (M)			
	Low (L)	Low (L)		
	High (H)	High (H)	High (H)	
101010	Maximum (X)	Maximum (X)	Maximum (X)	Maximum (X)
Number of retries	3	2	1	3

Table 1: States, power levels and retry limits.

has been chosen that supports single hop star topology. At the sensor node, an nRF24L01+ module is used that consumes a peak current of 11.3 mA at the maximum output power of 0 dBm. At the base station, the nRF24L01+ module has an additional power amplifier (PA) and a low noise amplifier (LNA). It has maximum output power level of 20 dBm. The transmitter counts a packet to be successfully transmitted if it receives an acknowledgement from the base station within a time window. A high power transmitter at the base station means that a practically error-free downlink can be ensured. A base station is assumed to be Mains powered and therefore energy savings is not relevant. Some of the features of the Nordic module are presented in Tables 1 and 2.

In general a wireless transceiver has different modes of operation. They are mainly divided into active transmit mode, active receive mode, standby mode and sleep mode. In between retries, a transceiver module usually goes to a standby mode without shutting down its transmitter units. The transceiver module used in the experiment also has different modes of operations. The output mode power levels and their corresponding current consumptions are tabulated in details of the different output modes and their current ratings are presented in Table 3.

Performance Parameters

The performance of any power control algorithm aimed at conserving energy is measured by the average cost of transmission per successful transmission (C_{savg}). SAPC also evaluates the protocol efficiency in terms of the average number of transmission per successful transmission. This parameter is equally important as it reflects the number of times the packet transmission has been repeated [28-30]. The packet success rate (PSR) is defined as the ratio of the successfully transmitted packets divided by the number of packets sent Mathematically,



Figure 4: State transition diagram of the adaptive algorithm.

Device: Receiver	nRF24L01+ with PA and LNA [35]	
Maximum output power	+ 20 dBm	
Transmission mode peak current	115 mA	
Reception mode peak current	45 mA	
PA gain	20 dB	
LNA gain	10 dB	
Device : Transmitter	nRF24L01+ [36]	
On air data rate	250 kbps	
Cyclic redundancy check	CRC-16	
Packet size	41 bytes	
Modulation method	Gaussian FSK	

Table 2: List of hardware and transmission parameters.

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

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Table 3: Operational modes and current consumptions of NRF24L01+.

$$PSR = 100 * \frac{P_s - P_L}{P_L}$$
(1)
Where,

P.: Number of lost packets

P_s: Number of packets to send.

$$C_{\text{Sarag}} = \frac{C_T}{P_S - P_L}$$
(2)
Where,

C_{Save}: Average energy cost per successful transmission.

 C_{T} : Total cost of transmission (first transmission attempt of a packet + the subsequent retries if the first attempt fails).

All cost values are measured in mJoules. *PS* – *PL* in equation 2 is the count of successfully transmitted packets.

The formula for protocol efficiency is shown in equation 3.

$$Protocol_{eff} (\%) = \frac{PSR}{1 + Ret_{xw}}$$
(3)

Where Retavg: average number of retries per packet and is defined as;

$$Ret_{avg} = \frac{Ret_T}{P_s}$$
(4)

Simulation Results and Analysis

The design of the simulation is to emulate the real world scenarios when the distance between the mobile sensor and the hub is varying with time. The different distances yield different Eb/No values and therefore not constant. Five random walks are simulated and the performance parameters of fixed power transmission are compared with the non-RSSI based adaptive protocol that is proposed in this paper. The walks that are simulated are one dimensional (1-D) random walks that takes a forward or a backward step with equal probability [31,32]. In simulation, the range of distance that the walk can cover has been restricted between -40 meters and 40 meters with the starting point set to 0 meter. Based on the Cost231 path loss model [33] that includes 4 Type-I wall partitions in between the sensor and the hub, the minimum Eb/N_o is approximately 0 dB at -18 dBm. In each position, the sensor transmits 20 times. Figure 5 shows the plot of the distance of 5 random walks in one dimension that are generated using MATLAB simulation [34].

When fixed power transmission is applied, there will be a power level which uses minimum energy per successful transmission while maintaining an acceptable PSR and protocol efficiency. It is referred to as the optimal power level. This value is limited by the available output power levels of a given RF transceiver [35-39]. The simulation is designed to investigate if SAPC can perform better than fixed power transmission when the sensor is subjected to ransom motion. Figures 6-20 compare these performance parameters.

Results from random walk 1

In general, the results of random walk 1 demonstrate the usefulness of the adaptive protocol in terms of saving energy. The energy saving







Figure 6: The PSR as the constraint parameter shows that both fixed power (above power level -12 dBm) and adaptive transmission strategy have comparable values (~100%).



less energy for a successful transmission on average. The power level for optimal energy consumption in fixed power mode is -6 dBm.



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Figure 8: The protocol efficiency at -6 dBm is a touch less than the adaptive protocol.



Figure 9: The PSR as the constraint parameter shows that both fixed power (above power level -18 dBm) and adaptive transmission strategy have comparable values (above 95%).



Figure 10: The cost comparison shows that the adaptive protocol consumes less energy for a successful transmission on average. The power level for optimal energy consumption in fixed power mode is -12 dBm.



Figure 11: The protocol efficiency of the adaptive protocol is 5.5% higher than at -12 dBm.



Figure 12: The PSR as the constraint parameter shows that both fixed power (above power level -12 dBm) and adaptive transmission strategy have comparable values (above 95%).



less energy for a successful transmission on average. The power level optimal energy consumption in fixed power mode is -6 dBm.



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Figure 14: The protocol efficiency of the adaptive protocol is a touch higher than the optimal fixed power level at -6 dBm.







Figure 16: The cost comparison shows that the adaptive protocol consumes less energy for a successful transmission on average. The power level for optimal energy consumption in fixed power mode is -6 dBm.







Figure 18: The PSR as the constraint parameter shows that both fixed power (above power level -18 dBm) and adaptive transmission strategy have comparable values (above 95%).



less energy for a successful transmission on average. The power level for optimal energy consumption in fixed power mode is -12 dBm.



is not significant (2.5%), but it provides hints that the adaptive power control can be an effective method of increasing the battery lifetime in the long run. The optimal fixed power is -6 dBm. It has comparable PSR and protocol efficiency values with the adaptive protocol at drop-off rate R of 0.05.

Results from random walk 2

The reason for the optimal power level has changed from -6 dBm in random walk 1 to -12 dBm in random walk 2 is because in random walk 1, the distance between the sensor and the hub has been more towards the extreme ends (40 meters), while in random walk 2, the distances are closer to the initial value (0 meter). Therefore, more energy was required in random walk 1 than random walk 2 to achieve the similar PSR. There is practically no difference in the cost values (~1%) because the optimal power level is lower than in random walk 1.

Results of random walk 3

The cost comparison in Figure 13 shows that the adaptive protocol is roughly 3% more energy efficient than transmission at fixed power of -6 dBm.

Results from random walk 4

The energy savings in random walk 4 is not significant and is around 2.3%.

Results from random walk 5

The energy savings in random walk 5 is approximately 6%.

From Figures 6-20 it is observed that the proposed adaptive protocol can save more energy than fixed power transmission. However, that also depends on the value of the drop-off factor R. Results show that at R value of 0.05, the energy efficiency can be achieved. These results provide the motivation to implement the adaptive protocol in hardware and test in real world environment.

Behaviour of the state transitions based on the drop-off factor R

In this section, the state changes due to random motion are plotted as a function of transmission when the transmitting sensor makes random motion along the red dotted line inside a University building as shown in Figure 21. The sensor was made to transmit after every 5 seconds. Therefore, essentially the snapshot duration is 25 minutes. Citation: Basu D, Gupta GS, Moretti G, Gui X (2017) Energy Efficiency Comparison of a State Based Adaptive Transmission Protocol with Fixed Power Transmission for Mobile Wireless Sensors. J Telecommun Syst Manage 6: 149. doi: 10.4172/2167-0919.1000149



Figure 21: Traversal path of the sensor is shown in dotted red line. The distance between the sensor and the hub is not constant.



drop-off rate is 0.01. The system toggles between different states less frequently even when link quality decreases (by increasing the distance between the sensor and the hub).

Figures 22-26 plot the states of the system for different drop-off factors (R).

The state change responses show that depending on the value of R the states will change fast or slow. When the distance increases, the path loss value increases and the system stay more often in a higher state. The value of R determines as to how fast or slow the states will switch. When R is 0.01, the system hardly change state when distance between the sensor and hub is large, as shown in Figure 22. On the other hand, when R is set at 1, the system bounces between the states more frequently (Figure 26). It is the ability of the system to switch to a lower state to start transmitting at a lower power that makes it energy efficient in the long run.

Experimental Results to Compare Performance of the Adaptive System with Fixed Power System when Sensors are Mobile within University Campus

In this section, the experimental results of the adaptive and fixed power transmission systems are presented. The design of the experiment is tabulated in Table 4.









The distance between the sensor and hub is changed with time. It has been a random walk during the busy hours inside the University campus building and was repeated 5 times. In some of the walks,

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Table 4: Experimental design to test the performance when sensors are mobile



Figure 25: State traversal with the number of transmission when exponential drop-off rate is 0.5.Even less time spent in higher states.



transmissions at a particular fixed power level did not deliver any packet at the receiver. Their results are not included in the figures.

Results of Figures 27-31 suggest that there is a significant reduction in the energy expenditure per successful transmission when adaptive power control is used as compared to fixed power transmission.

Conclusion

The results based on practical experiments are promising and demonstrates the usefulness of employing power control to achieve energy efficiency when sensor nodes are mobile. The advantage of the adaptive protocol is that it does not uses RSSI values for packet transmission. There are two distinct sections in the adaptive algorithm. One section guides the system to move up in the state when channel condition deteriorates so that high output power is required. The other section set the rule for dropping-off to a lower state using back-off algorithm. It is able to counter link quality changes that are transient or long term. The proper choice of the drop-off parameter R can



Figure 27: PSR, Efficiency and energy cost per successful transmission plots based on random walk in University campus. The optimal fixed power level is - 6dBm. The PSR of the adaptive protocol at R 0.5 is higher (97% as compared to 93%). The % efficiency is also better. The adaptive protocol at R 0.5 consumes 30% less power than at the fixed optimal power.





optimize energy efficiency. The experimental results indicate that the optimal energy consumption can be achieved if the R value is set at a value between 0.5 and 0.1. However, the simulation values suggest that the optimal energy consumption is achieved when R is set at around 0.05. This is based on the five random walks that were used in the simulation. Simulation results gave the preliminary indication that the adaptive protocol can help in saving energy. The simulations have their limitations because they are conducted in controlled environment. All the experiments were conducted both during the busy and non-busy hour of the University. Therefore the radio environment is not typically controlled. Rather, the radio link is more dynamic, both temporally



Figure 29: PSR, Efficiency and energy cost per successful transmission plots based on random walk in University campus. At optimal power level of 0 dB, the PSRs are comparable (~88%), the % efficiency values are the same at 60% while there is a reduction of approximately 25% in the cost.



Figure 30: PSR, Efficiency and energy cost per successful transmission plots based on random walk in University campus. The optimal power level is -12 dBm. The PSR values are comparable at greater than 95%. However, the % efficiency value of adaptive protocol at R 0.5 is much greater than at -12 dBm (95% as compared to 82%). The energy consumption per successful transmission is 20% less than when fixed power is used.



Figure 31: PSR, Efficiency and energy cost per successful transmission plots based on random walk in University campus. The optimal power level is 0 dBm. The PSR values are comparable (~97%), the % efficiency values are the same at 80%. While there is a reduction of more than 30% in cost when adaptive protocol at R 0.5 is used.

and spatially. The adaptive protocol is designed in such a fashion that it can squeeze in every opportunity to save energy.

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