Adaptive Power Control-based Energy Efficient Routing (APCEER) in Wireless Sensor Networks

by

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dedicated to my mother and my wife for their affectionate love and support

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ABSTRACT

Wireless sensor networks (WSNs), comprising of large numbers of tiny sensor nodes, find their applications in all aspects of human life. Some of these applications are surveillance and monitoring system, structural health monitoring, forest fire monitoring, habitat monitoring, border monitoring, combat zone monitoring, crop monitoring, medical care, security system, nuclear protection and measurement systems, biological applications, health applications, chemical attack recognition and the fields where wires could not be used. Sensor nodes used in WSNs are resource-constrained in terms of their radio range and battery power. In most of the applications it is very difficult to recharge their batteries. Therefore, they need careful energy management. Such energy management is also affected by the way the data from source to sink is routed. Performance metrics of routing protocols in wireless sensor networks are also different from those used in traditional networks. In contrast to traditional networks, energy is the major point of focus in the development of routing protocol in wireless sensor network. Optimized consumption of energy is thought to ensure a long lifetime for a wireless sensor network.

In this dissertation, the main focus of our work is to explore all possible energy efficient approaches for the problem of data routing through energy-constrained sensor nodes in wireless sensor networks. In the first part of the dissertation, a gradient of cost fields is exploited to explore the energy-efficient routes for the delivery of data from any source node to the sink. The proposed, GRAdient Cost Establishment (GRACE), routing strategy is based on two cost factors: energy and link quality. A routing path is selected if it contains both high-power nodes and good-quality wireless links. In other words, GRACE operates on the optimized selection of paths that have lowest costs in terms of energy and link quality. In this way, GRACE reduces both energy consumption and communication-bandwidth requirements and prolongs the lifetime of the wireless sensor network. Using theoretical analyses and computer simulations, it is shown that the proposed dynamic routing, GRACE, helps achieve the desired system performance under dynamically changing network conditions. A comparison of the proposed strategy, GRACE, with one of the best existing energy efficient routing algorithms GRAB has been presented which shows a better performance of GRACE over GRAB. Moreover, it is observed that operation initialization and status updation exert significant impact on the performance of a routing algorithm in a wireless sensor network. For this purpose, various modes of operation for updating status are explored and their impact is shown on the lifetime curves of GRACE strategy.

Although GRACE is an energy-aware routing protocol designed specially for resource constrained wireless sensor nodes, however, limited battery resource at a sensor node coupled with the hostile multi-path fading propagation environment makes the task of the network to provide reliable data services with an enhanced lifetime challenging. The focus of the second part of the dissertation is, thus, to propose an energy-aware routing protocol embedded with transmission power control (TPC) mechanism. In the second part, the main operation of the proposed strategy, Adaptive Power Control-based Energy Efficient Routing (APCEER), is two fold. On one hand, it tries to establish gradient-based energy-efficient routes from source to sink and on the other hand, it forces every node on the route to exploit the minimum possible power level to transmit data to its next-hop neighbor, while maintaining a reliable wireless link. This two-fold operation not only saves the energy of each and every sensor node in the network but it also reduces the network-wide communication interference significantly. This energy-saving results in an overall increase in network lifetime and transmission throughput of the network. Computer simulations and test bed measurements are presented that show that APCEER outperforms the existing energy-aware routing strategies, not equipped with a power control mechanism. It can thus be used in urban applications of wireless sensor networks where ultra-efficient utilization of energy, by power-constrained nodes operating in severe fading conditions, is needed.

LIST OF PUBLICATIONS

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C11. G. Ahmed, Noor M Khan, "A Dynamic Transmission Power Control Routing Protocol to Avoid Network Partitioning in Wireless Sensor Networks," in Proc. *4th International Conference on Information and Communication Technologies (ICICT 2011)*, pages 1-4, Karachi, Pakistan, 2011.

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C14. Z. Khalid, N. M. Khan and G. Ahmed. "Progressive Energy-Aware Routing Protocol for Wireless Sensor Network," in Proc. *3rd IEEE International Conference on Electrical Engineering (ICEE)*, pages 1-7, Lahore, Pakistan, March 2009.

C15. G. Ahmed, N. M. Khan and R. Ramer. "An Energy Efficient Routing Protocol for Wireless Sensor Networks Using Power Control Strategy," in Proc. *26th Progress In Electromagnetic Research Symposium (PIERS)*, Moscow, RUSSIA, August 2009.

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C18. N. M. Khan, I. Ali, Z. Khalid, G. Ahmed, and R. Ramer, "A Quasi Centralized Clustering Approach For Energy-Efficient And Vulnerability-Aware Routing in Wireless Sensor Networks," in Proc. *1st ACM International Workshop on Heterogeneous Sensor and Actor Networks (HeterSANet) Co-located with International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, pages 67-72, Hong Kong, China, May 2008.

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C22. G. Ahmed, Z. Khalid, N. M. Khan, and P. Vigneras. "An Energy Efficient and Vulnerability-aware Routing Protocol for Wireless Sensor Networks," in Proc. *2nd IEEE International Conference on Electrical Engineering (ICEE 2008)*, pages 1-5, Lahore, Pakistan, March 2008.

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LIST OF ACRONYMS

APCEER	Adaptive Power Control for Energy Efficient Routing
ATPC	Adaptive Transmission Power Control
BAM	Broadcast Acknowledgement Mode
CH	Cluster Head
CMLR	Cost Effective Maximum Lifetime Routing
GRAB	GRAdient Broadcast
GRACE	GRAdient Cost Establishment
GBR	Gradient Based Routing
LEACH	Low Energy Adaptive Clustering Hierarchy
LMA	Local Mean Algorithm
LMN	Local Mean Neighbor
LPR	Lifetime Prediction Routing
LQI	Link Quality Indicator
LURP	Local Update-based Routing Protocol
MODTPC	Modified On Demand Transmission Power Control
ODTPC	On Demand Transmission Power Control
PAR	Power-Aware Routing
PCBL	Power Control with Black Listing
PEGASIS	Power-Efficient Gathering in Sensor Information Systems
PRR	Packet Reception Rate
QCCA	Quasi Centralized Clustering Approach
RSSI	Radio Signal Strength Indicator
SS	Single Setup
TEEN	Threshold Sensitive Energy Efficient Sensor Network Protocol
TPC	Transmission Power Control
UAM	Unicast Acknowledgement Mode
WSNs	Wireless Sensor Networks

LIST OF SYMBOLS

Symbol	**Description**
E_{Tx}	Energy Consumption in Tx
E_{Rx}	Energy Consumption in Rx
E_{Lx}	Energy Consumption in Listening
i_{Tx}^{k}	Current Drawn by a node in Tx mode with Power Level k
i_{Rx}	Current Drawn by a node in Rx Mode
i_{Lx}	Current Drawn by a node in Listening Mode
$i_{\text{Pow}}^{\text{Green}}$	Current Drawn by power LED in Green
$i_{\text{Act}}^{\text{Green}}$	Current Drawn by activity LED in Green
$i_{\text{Act}}^{\text{Red}}$	Current Drawn by activity LED in Green
v	Voltage Level at which the Node is Operating
t_{Packet}	Transmit Time of a Packet
γ	RSSI
$\gamma_{\text{Th,Lower}}$	RSSI Lower Threshold
$\gamma_{\text{Th,Upper}}$	RSSI Upper Threshold
n	Path-loss Exponent
R_b	Data Rate
$Size$	Data Packet Size
f_c	Carrier Frequency
α_I	The advertisement information sent from node ’I’ to its neighboring nodes using APCEER
$C_{I\to S}$	The minimum-cost path from node ’I’ to sink ’S’. This shows the only available minimum-cost path using APCEER
$C_{I\to J\to S}$	The path from node ’I’ to sink ’S’ utilizing node ’J’ in the routing path. This represents actually a single specific path originating from node ’I’ out of many available paths terminating at sink ’S’ using APCEER
$\text{C}_{\text{E},i}$	Energy Cost of i^{th} Node using APCEER
$\text{C}_{\text{L},u\to v}$	Cost of a Link between node u and node v using APCEER
Ω_E	Weighting Factor of Energy Cost in APCEER
Ω_L	Weighting Factor of Link Costs in APCEER
E_i^0	Starting battery power of i^{th} node
E_i	Remaining battery power of i^{th} node
d_0	$\text{close} - \text{in} - \text{reference distance from the transmitting node to a point in the close proximity of the node}$
γ_0	$\text{received signal power at close} - \text{in} - \text{reference distance,}\ d_0$
d	$\text{transmitter} - \text{receiver separation}$
n	path loss exponent, dependent upon the propagation environment, varying from 2 to 6
h	channel state information
X_σ	uncertainty in the received power in dB due to any unknown random sources. $\text{This uncertainty is usually modeled as zero} - \text{mean Gaussian i.i.d.}$

	process with standard deviation, σ
$I_{\mathrm{E},i}$	Energy Impact Factor of node i in GRACE
C_{i-Sink}	Cost of the Path which heads to the Sink from i^{th} node using GRACE
C_{ij}	Cost of the Path which heads to the Sink via j^{th} node from i^{th} node using GRACE
A_i	Advertisement Packet Broadcasted by i^{th} node to its immediate neighbors using GRACE
β	Collective Performance Metric in GRACE
μ	Data Reliability in GRACE
e	Network Energy Left in GRACE
P_{LO}	Power Consumed by Frequency Synthesizer and VCO
P_{PA}	Power Consumed by the PA
P_{Out}	RF Output Power
η_{Pow}	Power Efficiency of the Power Amplifier
$P_{\mathrm{PA},i}$	Power Consumed by the PA for the i^{th} Transmit Interval Transmitting at a Specific Power Level, P_{Out}
$t_{\mathrm{Tx},i}$	i^{th} Transmit Duration
N_{Tx}	Number of Times Transmitter is Switched ON
t_{startup}	Constant Startup Time for the Local Oscillator to get Prepared for Transmission
$\omega(k-1)$	Gaussian Distributed Zero Mean i.i.d. Process with Variance Q_ω
α	Channel Autocorrelation Function Accounts for the Channel Doppler Spread
f_d	Doppler Frequency
T_s	Symbol Period
t_{Rx}	Receiving Duration
$t_{\mathrm{Rx},i}$	i^{th} Receiving Duration
t_{startup}	Constant Startup Time for the Receiver
N_{Rx}	Total Number of Times, the Receiver is Turned ON

Chapter 1

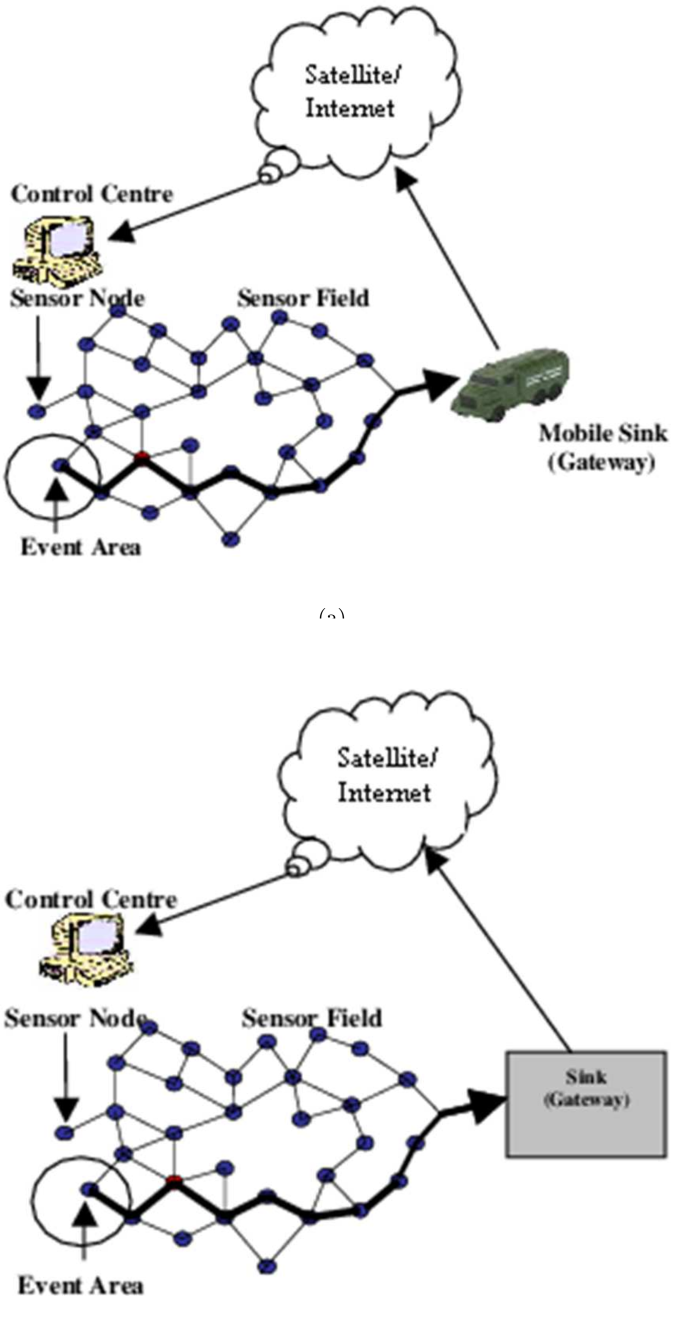
INTRODUCTION

1.1 Overview

Advancement in Micro Electro Mechanical Systems (MEMS) technology has enabled the development of tiny, relatively inexpensive, highly sensitive and sophisticated devices, called micro sensors. These can be connected via wireless links [1, 2, 3] to form Wireless Sensor Networks (WSNs). These sensor nodes (or simply nodes) are usually deployed randomly and densely in a hostile environment. Each sensor node contains micro sensor(s), a micro processor, Analog to Digital Converter (ADC), memory, radio, battery and a tiny OS which manages all these resources in an optimal way. Depending on the environment, sensor nodes recharge their batteries from ambient sources like solar energy [4]. However, the solar energy solution is not applicable in an area with little sunshine [5].

Wireless sensor networks are used in many indoor and outdoor application areas including health monitoring, security, factory automation, environmental monitoring, structural health monitoring and condition-based maintenance [6]. Furthermore, it is mostly used in areas where human intervention is not possible like monitoring active volcanoes, nuclear reactors and disaster sites.

Sensor nodes collaborate with each other to observe the surroundings and send their information back to the base-station in a multi-hop fashion. The base-station is a powerful node responsible for collecting information from the network when abnormal events occur, i.e., the base-station acts as a sink for all data traffic. The base-station (sink node) may or may not be a mobile node. In [7, 8], the authors use a term SENMA (Sensor Network with Mobile Access) for such mobile sinks, where a sink serves as a data carrier that transfers the sensor data. Hence,



(a)

(b)

Figure 1.1: Wireless Sensor Networks with (a) Mobile Sink (b) Stationary Sink

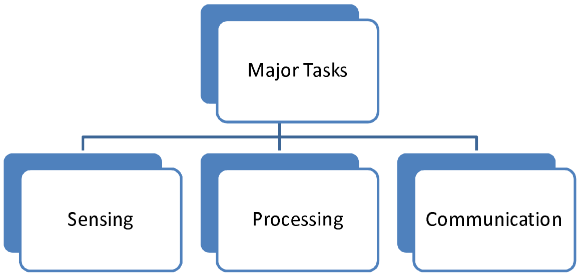


FIGURE 1.2: Major Tasks of a Wireless Sensor Node

the novelty of SENMA is the introduction of mobile agents which are powerful nodes with the capability of traversing the sensor network, along with a carefully designed trajectory [9]. In [10], the authors compared the performance metrics of fixed sinks with mobile sinks.

Figs. 1.1(a) and 1.1(b) represent the multi-hop WSNs with mobile sink and stationary sink respectively. Mobile sinks bring high data success rate and energy balance. The energy depletion of sensor nodes near the fixed sink is very high, however, in the case of the mobile sink, energy is evenly utilized among sensor nodes. This is due to the fact that mobile sinks can gather data from their nearby sensor nodes in either one-hop, where the energy consumption per bit is much lower due to direct communication with the mobile sink, or in multi-hop fashion, which provides low data delivery delay. Another advantage of mobile sinks is that it can approach disconnected sensor nodes; whereas with fixed sinks, such nodes cannot find a path to deliver their data to the sink. However, mobile nodes need complex procedures to control and manage their own operations. In addition, these can only be used in applications where deployment area is accessible to mobile nodes [5] [11]

A sensor node performs three major tasks as shown in Fig. 1.2: sensing, processing and communication. It collects the information from its surrounding, performs computation for decision making and sends it towards the sink [12]. Radio communication consumes more energy than sensing and processing. The transmission of one bit over 100 meters costs the same amount of energy as consumed by the execution of 3000 instructions [3]. Therefore, it creates the need for efficient utilization of radio communication circuitry to enhance the network lifetime.

The wired networks, unlike wireless sensor networks, are not limited by energy, node failure due to physical reasons, and lack of a centralized controller. It is, therefore, easier to design and model a real-time wired network system. However, due to inherent problems of multi-hop wireless sensor networks, the design of a routing protocol, which ensures both Quality of Service (QoS) and energy awareness [13], is a challenging problem. This is due to various reasons. Firstly, WSNs have lossy links that are greatly affected by environmental factors such as fading and shadowing, that occur due to the time varying nature of the propagation environment. As a result, communication delays are highly unpredictable. Secondly, many WSNs applications (e.g., border surveillance) require to operate for months without wired power supplies. Thirdly, in real-time applications, valuable information may have different delay requirements. For instance, authorities need to be notified sooner about high-speed motor vehicles than slow-moving pedestrians. To support such applications, a real-time communication protocol must adapt its behavior based on packet deadlines. Finally, due to the resource constraints of WSN platforms, a WSN protocol should introduce minimal overhead in terms of communication and energy consumption and should use only a fraction of the available memory to update the network's state.

Moreover, in order to deliver sensed data to the sink reliably over an error prone wireless channel with less energy consumption, there is a need of an energy efficient routing protocol. There are numerous ways to achieve this goal, out of which transmission power control (TPC) is a key technique. TPC is used to reduce radio interference, increase network connectivity and prolong network lifetime. In this dissertation, TPC strategy is exploited in routing data from source to sink while utilizing the minimum required power. In our proposed strategy, an optimized transmission power level of any individual sensor node with its neighbor nodes is estimated adaptively. This results in huge power savings as compared to existing traditional routing protocols where only maximum transmission power level is used for radio communication.

The correct allocation of transmission power is critical in WSNs for both long life of the sensor devices and efficient utilization of the limited wireless bandwidth [14]. On the other hand, transmitting data packets with maximum transmission power have two major drawbacks: the unnecessary drainage of battery and high interference. Therefore, it is needed that each sensor node transmits at lowest possible transmission power level provided the packet successfully reaches the destination [15]. It has been well understood that transmission of data consumes most of the energy of a sensor node, while sensing, processing and other computational activities of a sensor node do not require much energy. As stated earlier, according to Pottie *et al.* [3], 3000 instructions can be executed for the same cost as the transmission of one bit over 100 m. From CC2420 radio data sheet [16], 22.5 mWatts energy depletes when the transmission power is set to -7dBm. Transmitting data with high transmission power wastes energy when the link quality is good, while high packet loss results in transmitting data with low transmission power when the link quality is bad. In other words, changing transmission power to high level has both positive and negative effects. The positive effect is that it increases the reliability of the data packets and avoids disconnection of the network in severe fading conditions [15]; however, the negative effect is that it leads to develop high interference [17], enhanced contention, increased congestion and wastage of valuable energy.

Therefore, there is a need to determine the optimal transmission power in order to reduce energy consumption and increase the lifetime of the wireless sensor network. This is due to the fact that sending data to a nearby node requires only a minimum transmission power level provided the channel is good and there is no need to transmit to this nearby node with high power level as this leads to unnecessary drainage of battery power. Therefore, it is required to find an algorithm

which estimates appropriate transmission power levels for every neighboring node. In [18], the advantages of using power control strategy in wireless multi-hop networks are studied. However, estimating optimal transmission power is not an easy task due to the instability and unpredictability of the radio fading channels [19]. From the previous discussion, it is clear that transmission power control (TPC) enhances the functionality of wireless sensor networks through numerous aspects. TPC enhances the consistency of the link and improves the probability of successful data transmission with optimal lowest power levels [18, 20]. Hence, an efficient power control is needed which optimizes the transmit power to a level suitable according to link conditions. Power control is very useful for devices or scenarios where recharging is either not possible or limited. It is thus the TPC that increases the lifetime of the network [21]. Moreover, the spatial reuse of channels is possible due to strict power control, i.e., the same channel can be simultaneously used by sensor nodes at locations where interference is sufficiently low [22]. A typical transmission power control phenomena is shown in Fig. 1.3, where a source node *S* has two neighbors, N1 and N2. Node *S* uses different transmission power levels for both of its neighbors that depend on the power received by each node.
There are three levels of transmission power control algorithms [23]:

1. **Network Level**: All nodes in the network have equal transmission power level
2. **Node Level**: Each node in the network may use different transmission power level but all packets from the node will have the same power levels
3. **Packet Level**: Each node sends data packets with different transmission power levels

There are two cases of the transmission power control in terms of decision making [22]:

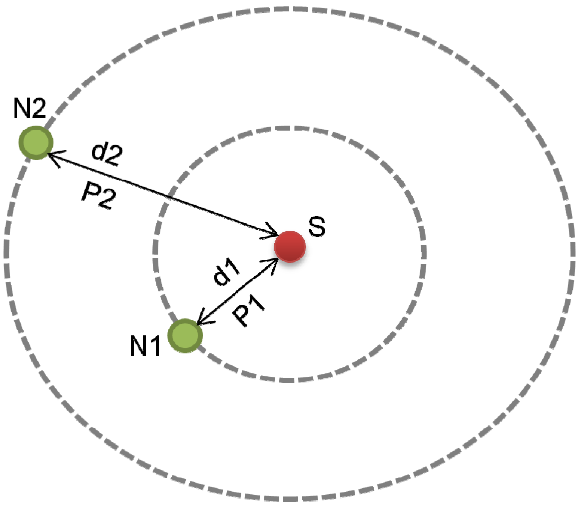


Figure 1.3: Different Transmission Powers of Node S with each of its Neighbor Nodes: N1 and N2

1. **Decentralized case**: Each sensor node selects its own power level depending upon the condition of its own radio channel.
2. **Centralized case**: The transmission power levels for all the nodes are selected by the sink or cluster head that has the complete set of information of all channel states.

The limited processing capacity and battery lifetime of sensor nodes in a wireless sensor network precludes the use of centralized schemes, thereby making decentralized approaches for power control more appropriate in such networks. Examples of some applications of decentralized approach are explained in [10, 24, 25]. A more extensive taxonomy and classification of transmission power control algorithms can be found in [26].

As far as the nature of wireless channels is concerned, they are highly uncertain due to the multipath fading in the propagation environment. Therefore, a node transmitting at relatively high power level may have a high data rate; nevertheless, its transmission may result in interference to other nodes. Thus, in order to avoid high packet error rates due to increased interference, the victimized nodes will attempt to maintain their signal to interference ratio by increasing their own transmission power levels. Such a situation is undesirable in wireless sensor networks where sensor devices are resource constrained and their batteries need judicious utilization. It is, therefore, required to control the transmit power levels in an optimal manner in order to increase both the data rate and the lifetime of the sensor nodes [22]. Hence, the uncertain nature of the fading propagation environment can be compensated by regulating the transmission power levels.

1.2 Problem Statement

From the discussion in section 1.1, we can conclude that the main problems in using the above-mentioned protocols include their large energy usage, raised communication interference due to their use of high transmission power levels, and short network-lifetime provision. Our research, thus, aims at providing the theoretical underpinnings and design principles for more energy-aware routing strategies that could provide larger throughput due to reduced interference and prolonged network lifetime.

1.3 Proposed Methodology

Aiming at extending the lifetime of the network along with reducing the energy dissipation of wireless sensor nodes, energy aware routing has been attracting extensive attention recently. It is motivated by the observation that high energy saving along with high data reliability can be achieved by using low and optimal transmission power levels which are based upon the distance between sender and receiver and the fading environment. The idea is to use the receiver's feedback to get an idea about the current channel condition based upon which transmission power is controlled for transmission of future data packets.

In areas where the channel does not change abruptly, energy can be saved and data can be sent reliably over unreliable wireless links by considering the energy of nodes and wireless link quality. Therefore, before starting the data communication phase, the energy and link costs of the network are propagated throughout the network. In this way, each node has information about the costs of reaching the sink through its neighboring nodes. The neighbor with the lowest cost is selected for routing data towards the sink.

1.4 Thesis Contribution

Specifically, the contributions of this dissertation can be summarized as follows:

1. An energy-aware routing strategy is proposed that is based on two cost factors: energy and link quality. In the proposed routing strategy, a gradient of cost fields is exploited to explore the energy-efficient routes for the delivery of data from any source node to the sink. The proposed strategy results in an overall increase in network lifetime. Theoretical results are confirmed through computer simulations.
2. A transmission power control-based energy-aware routing approach is proposed. Using the proposed approach, energy consumption in transmitting data from source nodes to the sink is reduced significantly. Computer simulations and testbed measurements are presented that show that the proposed approach outperforms the existing energy-aware routing strategies, not equipped with a power control mechanism. The proposed algorithm is thus suitable for urban applications of wireless sensor networks where ultra-efficient utilization of energy by power-constrained nodes operating in severe fading conditions is needed.

1.5 Dissertation Organization

The rest of the dissertation comprises of four chapters. Chapter 2 discusses the proposed GRAdient Cost-field Establishment (GRACE) routing protocol, which focuses on energy of nodes and link quality. The proposed protocol, GRACE, is presented with detailed description of the approach and discussions on different modes of operation.

In order to improve the performance of GRACE in terms of energy and lifetime of nodes, a transmission power control (TPC) strategy, Modified On Demand Transmission Power Control (MODTPC), is proposed in chapter 3. The benefits of TPC strategy in terms of energy saving is discussed in detail. Simulation results along with experimental results are also presented at the end of chapter 3.

Chapter 4 describes the Adaptive Power Control based Energy Efficient Routing (APCEER) protocol, which applies the idea of TPC on the energy-aware routing protocol, GRACE. Analysis of the impact of TPC on the routing protocol shows a remarkable improvement. In order to verify the theoretical analysis and to present benefits of the proposed approach, simulations along with an experimental study within real environment have been carried out.

Finally, chapter 5 concludes the dissertation and discusses future work.

Chapter 2

GRADIENT COST-FIELD ESTABLISHMENT (GRACE) ROUTING FOR WIRELESS SENSOR NETWORKS

As we know that energy is a crucial resource for widespread use of wireless sensor networks, it has become the mandatory goal of strategies designed for different levels of the protocol stack. Therefore, development of an energy-aware routing protocol is a big challenge. This chapter proposes an energy-aware routing protocol, GRACE, which is intended to enhance the network lifetime. The protocol has two main phases: setup phase and data communication phase. The former is related to cost field establishment throughout the network, while the path selection is performed in the latter phase which is based on residual energy of the nodes on a path. In this way, GRACE establishes gradient-based energy efficient routes from source to destination. The proposed routing strategy, GRACE, presents good results and outperforms the previous routing approaches like [27] [28] published in the literature so far.

The chapter begins with a thorough discussion on the existing routing protocols used in WSNs. Addressing one major shortcoming of the existing protocols [29] [30] i.e., unawareness towards energy utilization, has been set as the objective of our proposed work. Then the system model of the proposed routing strategy, its operation and various modes of updating status information are discussed. The simulation results, which are the central concern of performance evaluation for any wireless network, are then presented to support the design. Finally, the concluding remarks for the chapter are outlined.

2.1 Literature Survey

The general data collection problem in a given sensor network refers to the problem of routing the data collected by the sensor nodes to the sink as efficiently as possible keeping in view the awareness of time and energy. However, most of the conventional routing protocols do not consider energy or congestion at the forwarding nodes while routing a packet to its destination [13]. Therefore, no single routing protocol performs well in a complex real-world environment and the characteristics of WSNs, as discussed in Section 1.1, make the design of routing protocols challenging.

To address such challenges especially limited energy of WSNs, several analysis of energy efficiency of sensor networks have been conducted [31, 32, 33, 34] and several algorithms that lead to optimal connectivity topologies for power conservation have been proposed [35, 36, 37, 38, 39, 40].

In [13] and [41], the authors have discussed many routing approaches. One of the most common ways of ensuring real-time packet delivery is to flood the network with the information. However, flooding has extremely poor forwarding efficiency and results in redundant transmissions and increased energy consumption, hence decreasing network lifetime.

In GRAB [28], the authors focus on the problem of delivering messages from any sensor to an interested client user along the minimum-cost path in a large sensor network. In the design, authors present a backoff-based cost field setup algorithm [27] that searches the optimal costs of all nodes to the sink with one single message overhead at each node. Once the field is established, the message carrying dynamic cost information flows along the minimum cost path in the cost field. Each intermediate node forwards the message only if it finds itself to be on the optimal path, based on dynamic cost states. The design does not require an intermediate node to maintain explicit forwarding path states. It needs a few simple operations and scales to any network size.

A better approach is suggested in [42], where a set of disjoint paths is maintained from source to destination over which the data is transmitted. This scheme also results in substantial energy overhead and does not consider the time constraint nature of the packets. Certain schemes like [43] require GPS capability to find out the best route. The use of GPS receivers is not recommended in sensor nodes due to two reasons: First, since it is too expensive in terms of power consumption. Second, it is subject to failure when sensor nodes are deployed within some buildings or walls [41].

The SPEED protocol [44] achieves the goal of forwarding the packets closer to the destination and takes account of the presence of hot regions and congestion at forwarding nodes in its routing strategy. However, it does not take into account the energy of the forwarding nodes so as to balance the node energy utilization. Furthermore, the region it chooses for forwarding and the priority selection does not dynamically depend on the deadlines of the packets. SPEED also offers low reliability since it does not transmit any redundant data packets and uses a single route for data delivery. There are other strategies to choose an optimal path for real-time communication like minimal load routing [45], minimal hop routing, shortest distance path [46], etc. However, these strategies do not specifically support the stateless architecture and the energy constraint of the sensor networks.

The Power Aware Chain (PAC) [47] protocol achieves better network lifetime and is fault tolerant. It is also scalable and does not require geographic information to build the routing chain. However, it involves too much control overhead and complexity, plus the memory requirements are too high in the dense networks. PAC assumes that all nodes are capable of reaching the sink node which may not be possible in random deployment of sensor nodes.

Proactive Routing Protocol (PROC) [48] is used especially for real-time applications and used where continuous data is required. However, it is computationally expensive and involves high control overhead. It also has high memory requirements and the performance degrades in densely populated networks.

Efficient And Reliable (EAR) [49] routing protocol uses a proactive approach to build routes, and hence it is suited for real-time applications. It routes the data reliably, but the nodes around the hub (which collects the data from the network and forwards it to the base station) may deplete their energy too quickly. It also needs global identifiers which may not be feasible for large networks.

M. Chen et al. [50] recently proposed a routing protocol, named STEER (Spatial-Temporal relation-based Energy-Efficient Reliable routing protocol). In traditional approaches, a path is first established before data transmission. In a highly dynamic environment, the problem is that the path (or links, or next hop nodes) chosen at an earlier time may not work well during data transmissions after a while. In STEER, a packet is broadcast first and the node closest to the sink among those neighbors that receive the packet will be chosen as the next hop relay in a distributed manner. However, it is not bandwidth-efficient as a node broadcasts the data to each of its neighbors, thus uses most of the bandwidth.

In [51], the authors proposed a Local Update-based Routing Protocol (LURP) for WSNs with mobile sinks. In LURP, when the sink node moves, it only broadcasts its location information within a local area rather than the entire network, thus, it consumes less energy in each sensor node and also decreases the probability of collisions in wireless transmission. One major drawback of this protocol is that the sink broadcasts its location information to the entire network, whenever it goes outside the destination area. So if the network is large, the sink has to broadcast its location information to all the sensor nodes in the entire network, which takes a lot of time and the overall bandwidth consumption is also very high.

The single-gateway architecture can cause the gateway to overload with the increase in sensor density and this leads to communication delay and inadequate tracking of events [52]. Therefore, multi-gateway architecture is used, in which the network is partitioned into different clusters. Now, we are discussing some already proposed cluster-based routing protocols.

LEACH (Low Energy Adaptive Clustering Hierarchy) is a cluster-based routing

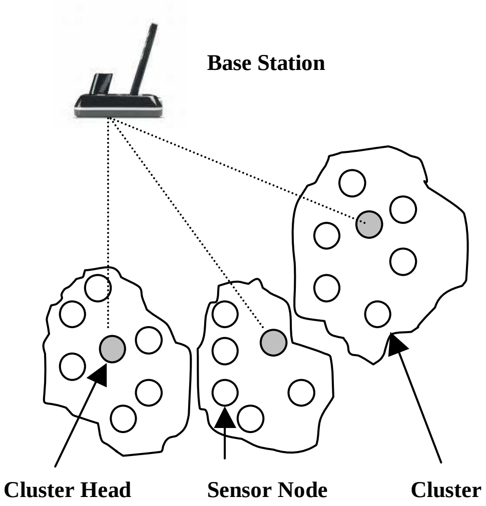


Figure 2.1: Cluster-based Wireless Sensor Networks

algorithm, proposed by Heinzelman*et al.* [39]. It is an energy-efficient communication protocol for WSNs. In LEACH, sensors self organize themselves into clusters; in each cluster, only a single cluster head transmits directly to the sink, while the rest of the sensors propagate data to their cluster head as shown in Fig. 2.1. Such protocols perform well in small area networks of low event generation rate; however in larger networks of high event generation rates, transmissions happen at large distances and the rotation of cluster heads may be too slow to avoid their energy depletion. The major drawback of LEACH is that it differs from the base station concept in current cellular systems in that it does not have special hardware for the cluster-head and, in fact, is dynamically selected among the set of stations. So, it does extra work with respect to ordinary stations, and therefore it may become the bottleneck of the cluster.

PEGASIS (Power-Efficient Gathering in Sensor Information Systems), an improvement over LEACH, is another example of an energy-aware protocol [53], which tends to increase the sensor network lifetime by decreasing the bandwidth via local collaboration among nodes. Another example is the TEEN (Threshold Sensitive Energy Efficient Sensor Network Protocol) proposed in [54]. Dynamic power management [55] has also been used for the design of energy-efficient wireless sensor networks. Other related work includes energy saving strategies for the link layer [56], data aggregation [57], and system partitioning [58].

The LEACH allows only single-hop clusters to be constructed. On the other hand, in [59] the authors proposed the similar clustering algorithms where sensors communicate with their cluster-heads in multi-hop mode. However, in these homogeneous sensor networks, the requirement that every node is capable of aggregating data leads to the extra hardware cost for all the nodes. Instead of using homogeneous sensor nodes and the cluster reconfiguration scheme, the authors of [34] focus on the heterogeneous sensor networks in which there are two types of nodes: super nodes and ordinary sensor nodes. The super nodes act as the cluster-heads. The ordinary sensor nodes communicate with their closest cluster-heads via multi-hop mode [60].

2.2 GRACE System Model

2.2.1 Model Assumption

We randomly deploy a large number of sensor nodes in a monitoring area, which sense the data and send it to the control center via stationary sink. We make the following assumptions:

- To simplify the energy analysis, the time for sending a certain amount of data is assumed to be the same as the time for receiving the same amount of data. The distance from the different nodes to the sink is ignored.
- All sensor nodes are assumed to be homogeneous, therefore the energy consumption for sensing is the same for each sensor node.

2.2.2 GRACE Parameters

Each sensor node is defined by a info-value pair. These info-value pairs are discussed here briefly. Interested reader is referred to [61] for details:

2.2.2.1 Energy Cost of Node, $I_{\mathbf{E},i}$

In order to increase the lifetime of wireless sensor networks, low energy nodes is avoided in routing. This is achieved by maintaining the energy cost of i^{th} node:

$$\mathrm{I}_{\mathrm{E},i} = \frac{\mathrm{E}_i^0}{\mathrm{E}_i} \qquad \textit{Eq (2.1)}$$

Where, E_i is the remaining battery power and E_i^0 is the starting battery power of i^{th} node. From the above formula, we can conclude that we should avoid those paths which contain nodes having high value of $\mathrm{I}_{\mathrm{E},i}$.

2.2.2.2 Link Cost, $\mathbf{I}_{\mathbf{L},u-v}$

The proposed strategy uses link costs that reflect the communication energy consumption rates at the two end nodes. The aim of the strategy is to maximize the lifetime of the network by carefully defining link cost as a function of receiving and transmission power using that link. The transmission-value is set initially same for all the nodes. The link cost between nodes u and v can be measured as follows:

$$\mathrm{I}_{\mathrm{L},u-v} = \frac{\mathrm{P}_{\mathrm{t},u}}{\mathrm{P}_{\mathrm{r},v}} \qquad \textit{Eq (2.2)}$$

Where, $\mathrm{P}_{\mathrm{t},u}$ is the transmission power of node u and $\mathrm{P}_{\mathrm{r},v}$ is the received power of node v. For convenience in use, we will represent $\mathrm{I}_{\mathrm{L},u-v}$ as I_{L} from now onward. Intuitively, a link that has high value of I_{L} means that there exist more chances of packet drop and more transmission energy would be required to overcome the hindrances of the path. So we can conclude that we should avoid such links that have higher values of I_{L}.

2.3 Phases of GRACE

2.3.1 Setup Phase Algorithm

Most of the wireless sensor networks routing strategies are data-centric. In data-centric strategies, sink sends interest packets to the area in the sensor field where it wants to collect the data. However in our strategy, which is more generalized as compared to the data-centric approach, the sink initiates the setup phase for the entire wireless sensor network. In the setup phase, a cost propagates throughout the sensor field. This cost field is established using the advertisement packet. Let,

- C_{i-Sink} be the cost of the path which heads to the sink from the i^{th} node
- C_{ij} be the cost of the path which heads to the sink via j^{th} node from the i^{th} node and
- A_i be the advertisement packet broadcasted by i^{th} node to its immediate neighbors.

The cost field propagation is better understandable by an example: As shown in Fig. 2.2, nodes j, k and l are the immediate neighbors of the i^{th} node. We can define the cost fields and advertisement packets as under:

$$\begin{aligned}
A_j &= C_{j-Sink} + \mathrm{I}_{E,j} \\
A_k &= C_{k-Sink} + \mathrm{I}_{\mathrm{E},k} \\
A_l &= C_{l-Sink} + \mathrm{I}_{\mathrm{E},l} \\
C_{ij} &= A_j + \mathrm{I}_{\mathrm{L},i-j} \\
C_{ik} &= A_k + \mathrm{I}_{\mathrm{L},i-k} \\
C_{il} &= A_l + \mathrm{I}_{\mathrm{L},i-l} \\
C_{i-Sink} &= \min(C_{ij}, C_{ik}, C_{il})
\end{aligned}$$

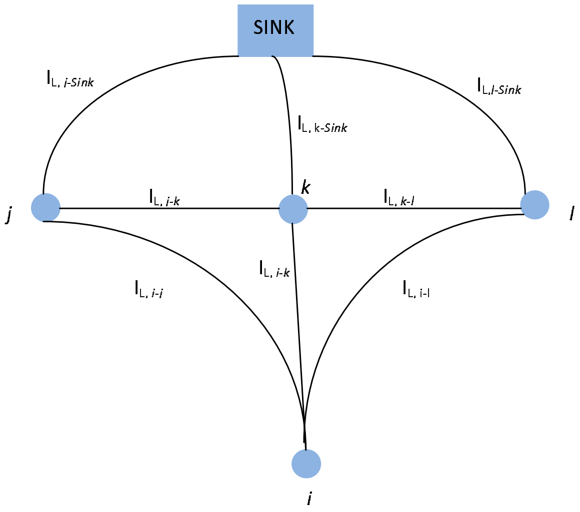


Figure 2.2: Cost Field Establishment

Initially $C_{node-Sink}$ is set to infinite for all the nodes in the sensor field. The sink initiates the setup phase by broadcasting the advertisement packet containing the cost $A_{Sink} = 0$ to all of its immediate neighbors. When a node receives the advertisement message with the cost, it stores the cost in its routing table. Then it calculates the link cost $\mathrm{I}_{\mathrm{L},node-Sink}$, as described in equation (2.2). Thus, a node's routing table contains cost C received from each of its immediate neighbors along with the neighbors' id. Now, the receiving node (say i) picks the smallest C value from its routing table, add its own $\mathrm{I}_{\mathrm{E},i}$ cost in it and broadcast this final value A_i to all of its immediate neighbors. Also, the receiving node considers the smallest value node as the relay node to send data back to the sink. The similar algorithm is running on other nodes and this process continues till the last node of the sensor field. Once the setup phase is completed, the steady state phase is performed to find the best path.

2.3.2 Steady-State Phase Algorithm

After the completion of the setup phase, the source node sends the data to that particular node which has smallest cost C value in its routing table. The receiver

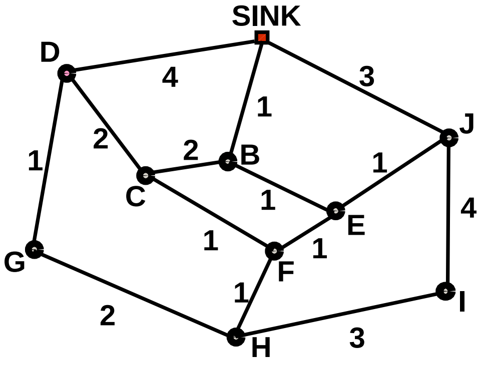


Figure 2.3: Example Scenario

then forwards the data to that node having smallest cost C value in its routing table and the same process continues till the data reach to the sink. In order to update the status information of sensor nodes, we propose different modes of operations that will be discussed in detail in Section 2.5.

2.4 Example Scenario

The setup and steady-state phases can be better understandable if we take an example. Let's take an example network as shown in Fig. 2.3. The energy levels and the link costs are calculated using equation (2.1) and equation (2.2) respectively. First the sink node broadcasts the advertisement message to nodes B, D and J. This advertisement message contains the cost A_{Sink}=0. Nodes B, D and J receive the message, calculate their respective link costs $I_{L,B\text{-}Sink}$, $I_{L,D\text{-}Sink}$ and $I_{L,J\text{-}Sink}$, then add their link costs to A_{Sink} to form C_{B-Sink}, C_{D-Sink} and C_{J-Sink} respectively. Nodes B, D and J store these information in their routing tables, as shown in Table 2.2. After a certain period of time, which depends on these costs as discussed in [28], the nodes select the minimum cost C_{x-Sink} from their routing tables, add their own energy cost $\mathrm{I_E}$ in it using Table 2.1 and broadcast it to all of their immediate neighbors (In Fig. 2.3 node B broadcasts its advertisement A_B to nodes: Sink, C and E. Node D broadcasts its advertisement A_D to nodes: Sink, C

Table 2.1: Energy Levels of Nodes at some time after the Deployment of the Network

ID	Sink	B	C	D	E	F	G	H	I	J
I_E	0	2	3	4	5	6	7	8	9	10

and G. Node J broadcasts its advertisement A_J to nodes: Sink and I). The same procedure also runs at nodes G, C, E and I. This process goes on one after the other according to their intervals, till the last node of the sensor field establishes its routing table. After the setup phase, steady-state phase begins. We take node H as a source node. Now node H looks for the node in its routing table which has the smallest cost C. In our case, it is node F. Thus, node H sends the data to node F. Same decisions for forwarding data are made on other nodes. In this way, data reaches the sink with minimal routing overhead.

2.5 Modes of Operation for Updating Status Information

We propose various modes of operation for updating status information of sensor nodes in wireless sensor networks. The performance of any routing strategy depends on the use of any particular mode. In this section, we present the behavior of our proposed routing strategy under the operation of these modes. These modes of operation are given below:

1. Single Setup (SS) Alone Mode
2. Unicast Acknowledgement Mode (UAM)
3. Broadcast Acknowledgement Mode (BAM)
4. Correction Mode (starting from the sink)
5. Correction Mode (starting from the intermediate node)

Table 2.2: Cost Fields in Routing Tables

i^{th} Node	Neighbor j^{th} Node	A_j	$\mathrm{I}_{\mathrm{L},i-j}$	C_{ij}	C_{i-Sink}	$\mathrm{I}_{\mathrm{E},i}$	A_i
B	Sink	0	1	1	1	2	3
	C	8	2	10			
	E	9	1	10			
D	C	8	2	10	4	4	8
	Sink	0	4	4			
	G	16	1	17			
J	E	9	1	10	3	10	13
	Sink	0	3	3			
	I	26	4	30			
C	D	8	2	10	5	3	8
	B	3	2	5			
	F	15	1	16			
E	J	13	1	14	4	5	9
	B	3	1	4			
	F	15	1	16			
F	E	9	1	10	9	6	15
	C	8	1	9			
	H	22	1	23			
G	H	22	2	24	9	7	16
	D	8	1	9			
H	I	26	3	29	16	8	22
	G	16	2	18			
	F	15	1	16			
I	H	22	3	25	17	9	26
	J	13	4	17			

The setup phase will be run at startup and information update will be made according to the operation of these modes. The plots showing the behavior of these modes on the performance of the network would consequently be used for choosing the best mode of operation for the information update procedure.

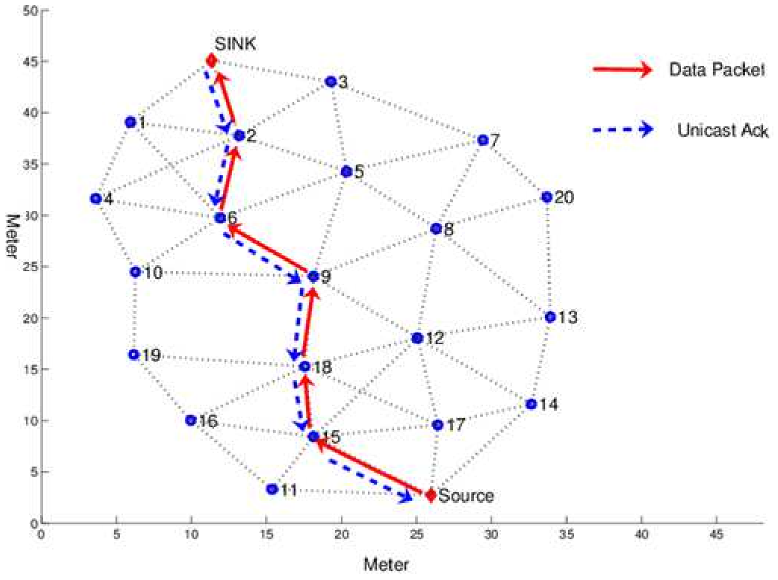


FIGURE 2.4: Unicast Acknowledgment Mode (UAM)

2.5.1 Single Setup (SS) Alone Mode

In this mode of operation, the setup phase runs only once at the startup. Thus later on using this mode, there is no mechanism to update the status information of sensor nodes. This leads to the continuous usage of a routing path till any of the node in the path dies.

2.5.2 Unicast Acknowledgement Mode (UAM)

Since every node has cost factors of its neighbor nodes. It selects node for routing data that has minimum cost. Later on, this cost factor is updated in such a way that the receiving node sends an acknowledgement to the sender whenever it receives the data. This acknowledgement comprises of one extra byte, showing the current minimum cost factor of the receiver node. Thus, the updates propagate in the sensor field by sending acknowledgments for the received data. Fig. 2.4 shows the unicast acknowledgement mode. In case of death of a node, its neighbor selects the second minimum cost neighbor for further data transmission.

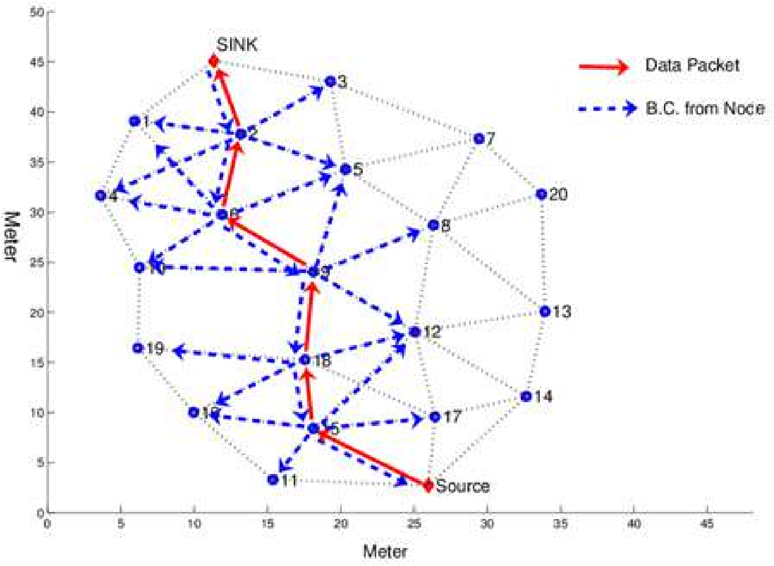


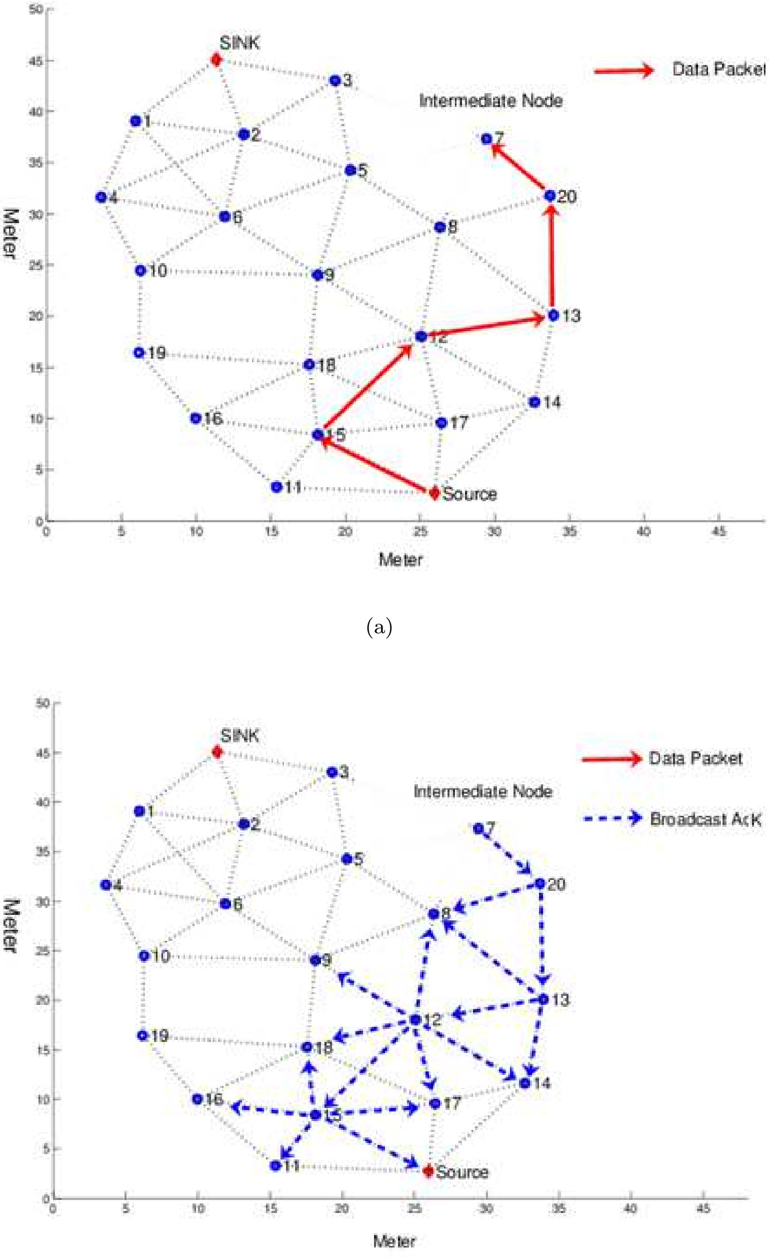
Figure 2.5: Broadcast Acknowledgment Mode (BAM)

2.5.3 Broadcast Acknowledgement Mode (BAM)

One major drawback of the acknowledgement phase is that only the sender knows about the updated status information of the receiving node. In order to avoid this, the receiving node can broadcast the acknowledgement along with its updated status information to all of its immediate neighbors. In this way, a node can inform all of its neighbors about its updated status information. Fig. 2.5 shows the broadcast acknowledgement mode.

2.5.4 Correction Mode (Starting from the Sink)

Whenever a node sends data packet to another node, it keeps the packet ID in its buffer. Similarly, every node gets a list of all the packet IDs it receives. Whenever a packet reaches the sink, it sends the acknowledgment to the node from which it receives the packet. That node then broadcasts the acknowledgement containing its updated status information to all of its neighbors along with data packet IDs. The packet ID will help recognize the corresponding node among the neighbors

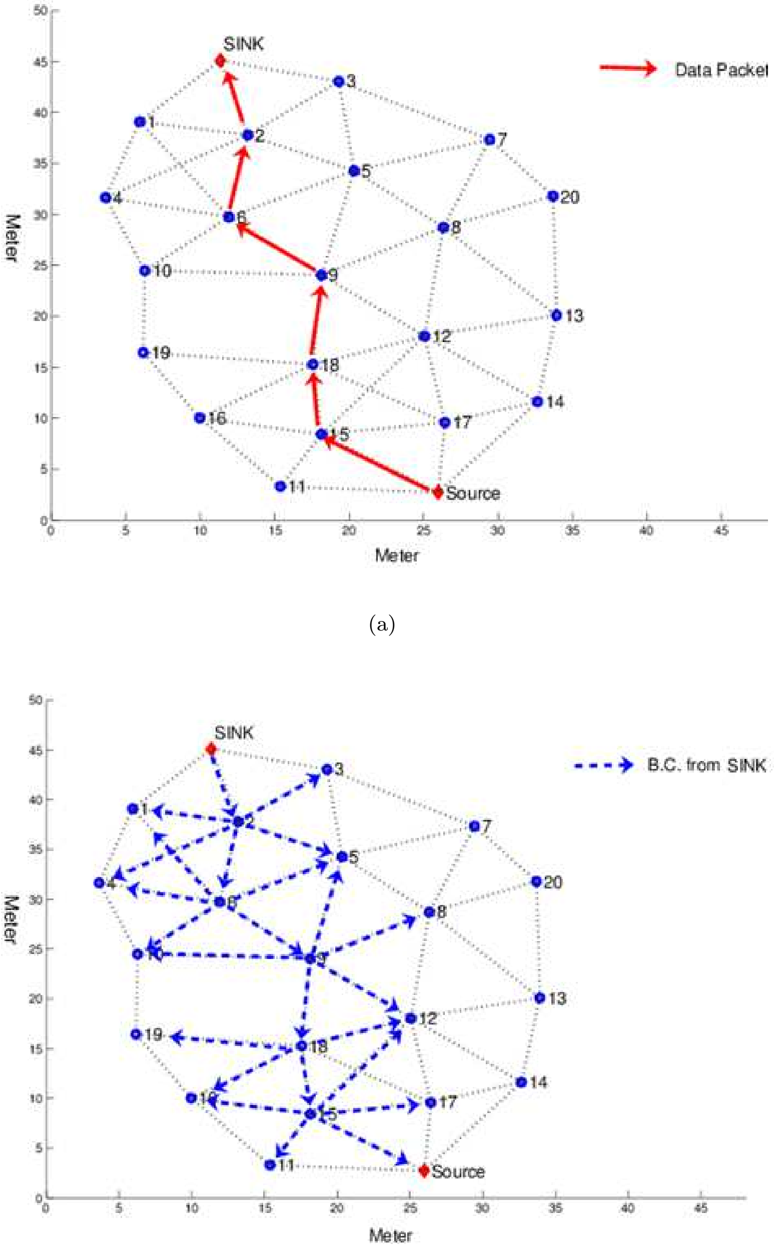


(a)

(b)

Figure 2.6: Correction Mode (Starting from the Intermediate Node) (a) Data Packets (b) Acknowledgment Packets

which took part in carrying that packet. This process will continue till the source node which originated the data packet, get the corrected cost of the path used in



(a)

(b)

Figure 2.7: Correction Mode (Starting from the Sink) (a) Data Packets (b) Acknowledgment Packets

carrying its data. Storing packet IDs gives an extra burden to the node memory. In order to minimize this burden, node will use a specified memory for packet ID storing on FIFO basis. Consequently, in case of congestion in a particular region of the network, node will lose the packet ID from its memory and hence will stop broadcasting for not allowing an increase in the congestion. Fig. 2.7(a) and Fig. 2.7(b) show the Correction Mode (starting from the sink).

2.5.5 Correction Mode (Starting from the Intermediate Node)

Sometimes the packet is lost or dropped at some intermediate node. In this case the correction mode will not be initiated as the packet has not reached at the sink. Therefore there must be a mechanism which initiates the correction operation at any intermediate node, so that the updated cost field is propagated along the entire path. Correction operation starting from the intermediate node is a solution for it. Fig. 2.6(a) and Fig. 2.6(b) show the Correction mode (starting from the intermediate node).

2.6 Results and Discussion

2.6.1 Simulation Setup

To investigate the performance and the scalability of the proposed protocol, we generate a sensor network comprising of 250 nodes and carry out extensive simulations in order to validate the proposed routing strategy under different modes of operation. Our sensor field's dimension is 0.0025 Kilometer Square. The simulation results are based on randomly deployed static wireless nodes. Nodes transmit data in a contention-based mode using CSMA/CA. The numerical values chosen for our simulations can be seen in Table 2.3.

Table 2.3: Parametric values used in Simulations

Parameters	**Value**
Number of nodes	250
Initial energy	97 J
Communication Range	200 m
Sensor field size	50x50 m^2
Data rate	250 kbps
Energy Consumption in Tx	14.87 mJ
Energy Consumption in Rx	15.39 mJ
Energy Consumption in Listening	3.5 mJ
Data Packet Length	1260 Bytes
Carrier Frequency	2.4 GHz

2.6.2 Performance Metrics

A set of performance metrics is used for evaluating the performance of the proposed strategy. One point that should be kept in mind is the degree of goodness or badness of the results. It clearly depends upon the working life of network. A network having only one established path from source to sink is much better than a network that has got large number of disconnected nodes scattered in a field. This takes us to the strategy that utilizes the network nodes on a uniform balanced manner. Another criterion that promises the reliability and useability of the network is preventing the nodes from dying till a large number of nodes die out collectively. The collective death of a large number of nodes will ensure a reliable data delivery and network operation for a specified time. This time would thus give us a prediction about the safe operation of the network. The use of network beyond this time would make its operation unreliable and unpredictable.

The given figures show the result obtained under various scenarios and modes of operation.

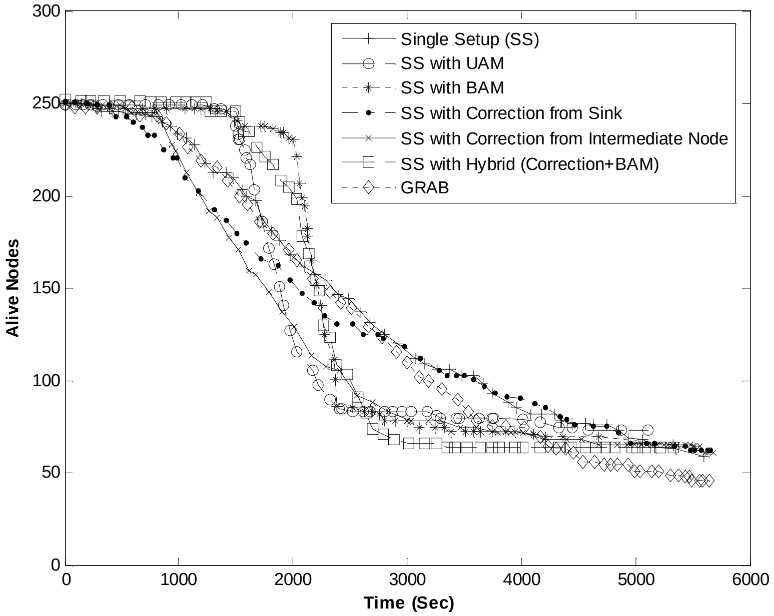


Figure 2.8: Network Lifetime: SS Alone, SS with UAM, SS with BAM, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB

2.6.2.1 Network Lifetime (in terms of Node Failures, f)

It shows how much time the network will stay alive. In Fig. 2.8, number of alive nodes is plotted against simulation time units. In these simulations, different modes of operation are used as discussed in Section 2.5. It can be seen that the correction mode from intermediate node has the lowest working life while the broadcast acknowledgement mode has highest working lifetime, thus keeping a large number of nodes alive with high data rate and reliable data delivery. The reason of this difference in results is that setup phase with the broadcast acknowledgement uses the nodes evenly in terms of energy utilization, while the other approaches like GRAB [28] do not ensure a balance utilization of nodes. In Fig. 2.9, we draw a bar graph for node failure, f (in percentage), versus time elapsed. It is also clear from the plot that when first node dies, single setup with unicast acknowledgement mode has longer time elapsed, while the single setup mode and GRAB [28] has the lowest time elapsed. This is due to the fact that in

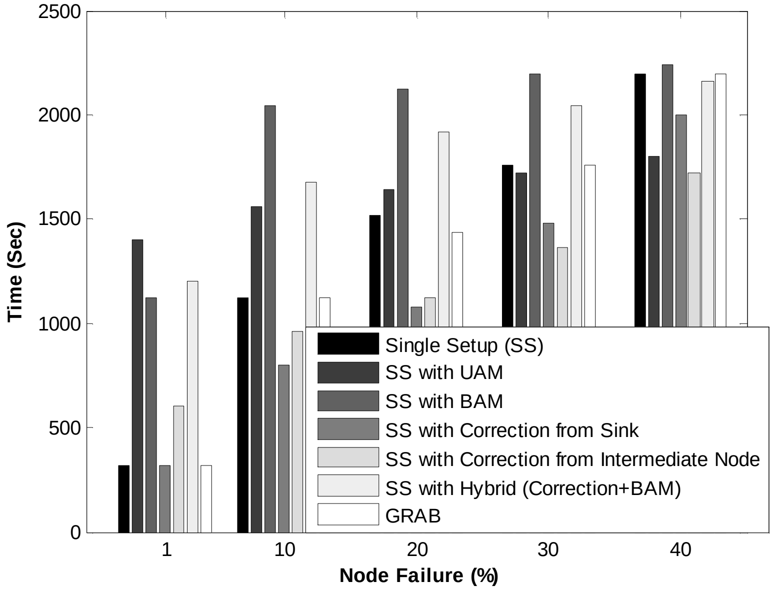


Figure 2.9: Node Failure in Percentage: SS Alone, SS with Unicast, SS with Broadcast, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB

case of single setup mode, which is based upon the initial nodes' status information, it continuously uses a path till any of the nodes in the path dies. While in case of GRAB [28], the setup phase will not run till the occurrence of any event.

2.6.2.2 Network Energy Left, *e*

It shows the amount of energy left, e, in the alive nodes whether connected or disconnected in the network with the passage of time. Fig. 2.10 shows plots of the network energy versus simulation time. From the figure, it is clear that use of single setup mode outperforms the others if energy consumption is considered. This is due to the fact that the setup phase runs only at the startup and no acknowledgment and correction is done at later times. Although this mode is good in the energy consumption sense but as a result of not using acknowledgement and correction, it loses data reliability as compared to other modes.

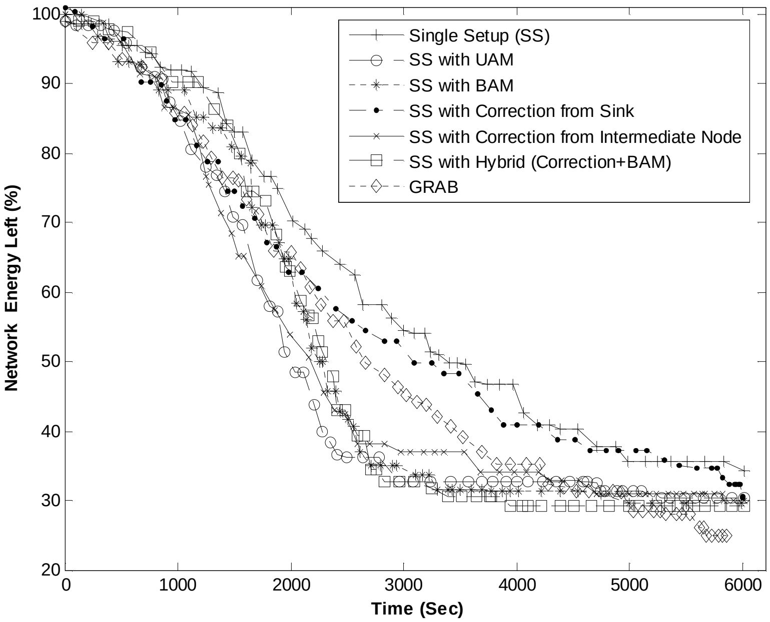


Figure 2.10: Network Energy Left: SS Alone, SS with UAM, SS with BAM, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB

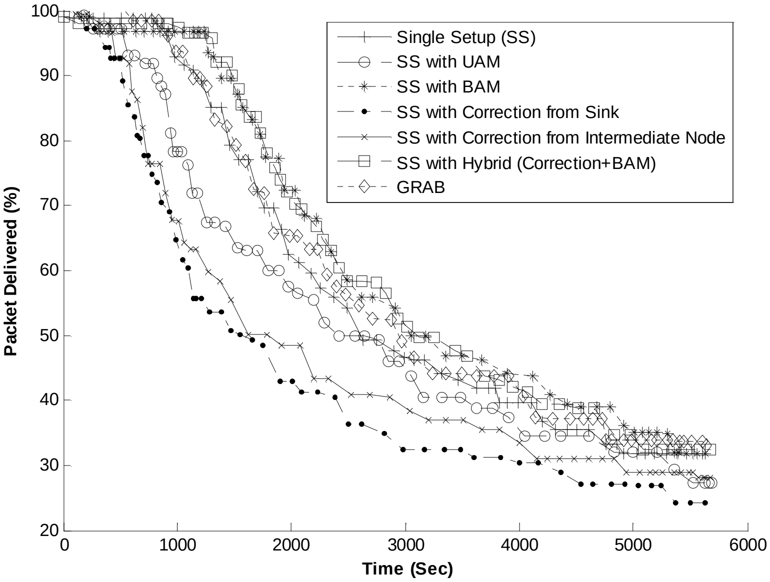


Figure 2.11: Data Delivery in Percentage: SS Alone, SS with UAM, SS with BAM, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB

2.6.2.3 Data Reliability, μ

It shows the success ratio of the data packets, i.e. the number of data packets received by the sink out of the total number of data packets generated by the source. In Fig. 2.11, one aspect of data reliability comparison is shown, where the plots represent the percentage data delivery with respect to simulation time. It is clear from the figure that the hybrid approach and the single setup with broadcast acknowledgement have high data reliability. This is due to the fact that the status information of the sensor nodes is updated frequently in these modes of operation. Another aspect of data reliability comparison is shown in Fig. 2.12, where the plots show an interval-based data delivered to the sink after a specified time interval (e.g, after each 100 seconds in our case), we note down the number of data packets received at the sink. It can be noted from the plots that initially the single setup with broadcast acknowledgement mode has highest percentage of delivered packets to the sink, but cannot keep its pace at later times and degrades its performance due to bulk node failures.

2.6.2.4 Efficiency (Collective Performance Metric, $\beta = \boldsymbol{f} \times \mu \times \boldsymbol{e}$)

The collective performance metric, β, can be used to reflect the network energy left, reliability and the node failures. It is clear from the Fig. 2.13 that the hybrid approach and the single setup with broadcast acknowledgement have high value of this metric. As discussed earlier, this is due to the fact that the status information of the sensor nodes is updated frequently.

2.7 Conclusion

In this chapter, we have proposed an energy-aware routing strategy named GRAdient Cost-field Establishment (GRACE) for wireless sensor networks. The proposed routing strategy outperforms the well-known event-based cost field establishment scheme, GRAB [28], with an enhanced network lifetime and more reliable data

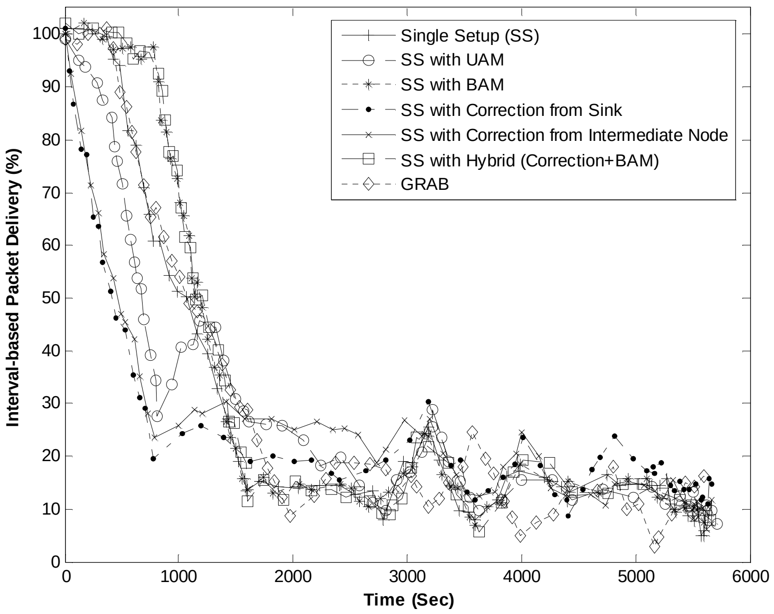


Figure 2.12: Interval-based Data Delivery in Percentage: SS Alone, SS with UAM, SS with BAM, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB

delivery. The comparison shows a better performance of GRACE over GRAB. The setup mechanism governing the GRACE scheme has also been discussed in detail. Various modes of operation for updating status information of the sensor nodes have been indicated. Moreover, some performance metrics have been set to evaluate the performance of WSNs.

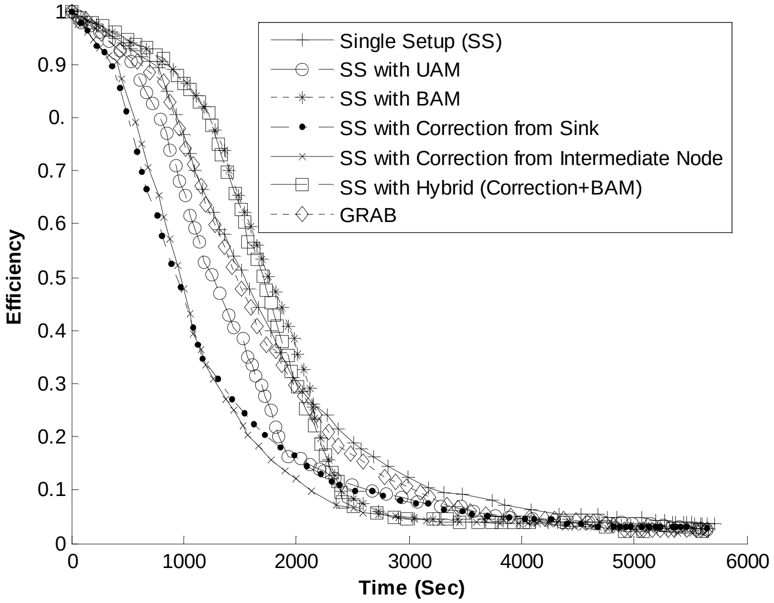


Figure 2.13: Collective Performance Metric, β: SS Alone, SS with UAM, SS with BAM, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB

Chapter 3

TRANSMISSION POWER CONTROL IN WIRELESS SENSOR NETWORKS

3.1 Introduction

3.1.1 Overview

Extensive research efforts have been going on to design energy efficient systems. Researchers are, therefore, trying to develop such strategies that could increase the network lifetime. Among different strategies that have been evolved, transmission power control (TPC) is a key technique. The main benefits of TPC is to achieve high energy saving, reduce radio interference, maintain good reliability of wireless links and provide high Packet Reception Rate (PRR). There are many TPC techniques available in the literature. However, these suffer from a common major deficiency i.e., existing TPC techniques are not energy efficient as these techniques are not optimized in terms of power level adjustment in accordance with the realistic situation [62].

The idea behind TPC strategy is that the transmission power is not always set to maximum; rather an optimum power level for transmission is find out with mutual coordination between transmitting and receiving nodes by establishing necessary feedbacks. The feedback sent by receiver lets a transmitting node decide if the transmission power level is needed to be modified or not. In case if there is a need to change the power level then up to what extent in order to attain the optimum transmission power level to achieve both objectives i.e., life time enhancement of network and better PRR. In Fig. 3.1, four nodes are shown: $n1$, $n2$, $n3$ and n,

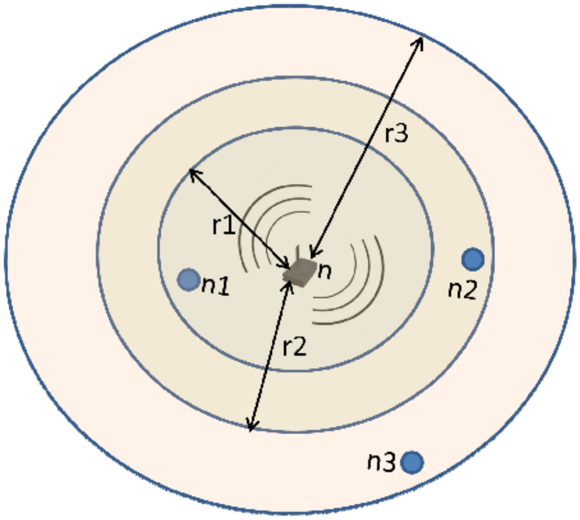


Figure 3.1: Transmission Power Control Mechanism in Wireless Sensor Network

where n is acting as the transmitting node. Node n uses three available transmission power levels, tp_1, tp_2 and tp_3, in order to transmit data packet to nodes at distances, $r1$, $r2$ and $r3$ respectively. Thus, if n needs to send a packet to n_1, transmission power level tp_1 suffices; however, tp_1 is not sufficient to send packets to $n2$ and $n3$; therefore, n defines three different power levels for each of its neighboring nodes for efficient energy utilization and getting optimum PRR. Let us consider a packet is transmitted by n towards $n2$; if tp_1 is used then the packet may be lost; on the other hand, if tp_3 is used then power is wasted unnecessarily. Therefore, only tp_2 serves as the optimum power level for this particular case. In this way, maximum energy can be saved without degrading the PRR.

Once the optimum transmission power level is set, it undergoes a continuous change depending on channel behavior and receiver's feedback. The feedback serves as an ensuring factor to certify that the transmission power does not deviate much from the optimum transmission power level.

In this chapter, a well-known TPC algorithm, On Demand Transmission Power Control (ODTPC) [19], is modified and enhanced. We name this modified version as Modified On Demand Transmission Power Control (MODTPC).

3.2 Related Work

There are many existing work on transmission power control. In this section, some of these works are discussed. The main goal of transmission power control algorithms is to find the optimal power for each neighboring node. Hence in such algorithms, power level switches among different transmission power levels.

Santi *et al.* [63] proposed a well-known topology control technique for wireless ad hoc and sensor networks. The purpose of the proposed technique is to reduce energy consumption and/or radio interference. This is achieved by dynamically controlling a node's transmission range. Moreover, this topology control approach results in reduced contention when accessing the wireless channel.

In Power Control with Black Listing (PCBL) algorithm [64], an initialization phase runs periodically. In this phase, each node sends certain number of beacon messages to each of its neighbors at a particular power level. This process repeats for all available power levels. After getting a specified number of packets at each power level, receiver node notifies the sender about the PRR of each power level. This notification message goes along with acknowledgement. Based on this notification, sender chooses the minimum power level that has 100% PRR.

Adaptive Transmission Power Control (ATPC) algorithm [65] also uses an initialization phase in which sender sends a beacon message to all of its neighbors at each power level. Receiver calculates the Link Quality Indicator (LQI) and received Radio Signal Strength Indicator (RSSI) of each of these beacons and sends these values back to sender along with acknowledgement. Upon receiving the RSSI/ LQI values, the sender node determines the optimal power level. Then runtime tuning phase starts, in which a sender sends the data packet to a receiver. The receiver node notify the sender only if the particular RSSI/ LQI value exceeds or falls below a given threshold boundary.

Both PCBL [64] and ATPC [65] have initialization phase overhead. In addition, as the channel changes very frequently, RSSI values are not enough to adjust the optimal power level.

In contrast, On Demand Transmission Power Control (ODTPC) [19] does not use any initialization phase. Whenever sender wants to send data to any of its neighbor, it sends the data and the receiver calculates the corresponding RSSI values. If this value exceeds or falls below a given threshold boundary, receiver notifies the sender via notification message. Based on this notification message, sender adjusts its power level. Although ODTPC [19] does not use any initialization phase, its response is not as fast as the channel changes its state due to multi path fading.

In [21], Ares *et al.* proposed two power control algorithms: Multiplicative-increase Additive-Decrease power control (MIAD PC) and Packet Error Rate Power Control (PER PC). PER PC based on signal to inference plus noise ratio (SINR), while MIAD PC sets the transmission power level based on the PRR. A systematical model of the wireless channel has been developed to approximate SINR in PER PC algorithm.

3.3 Proposed Transmission Power Control - Modified ODTPC (MODTPC)

3.3.1 Assumptions

In designing MODTPC, we assume the following

- Sensor nodes are homogeneous in terms of battery power and processing capability
- Radio has the ability to adjust its transmission power levels
- Sensor nodes are 802.15.4 compliant

3.3.2 Proposed Methodology

ODTPC [19] strategy is based on RSSI in order to find the optimal transmission power level. Here, RSSI is denoted by γ. At the beginning, whenever a node has a data packet to send, it uses maximum transmission power level. After receiving the data packet, receiver piggybacks the computed RSSI value with the acknowledgement and send it to the transmitting node. Based on this RSSI value, the transmitter adjusts its transmission power level with the receiving node according to the strategy discussed below.

In ODTPC [19] strategy, a RSSI region is established prior to the start of the algorithm. This region is bounded with two threshold levels of RSSI i.e., $\gamma_{\text{Th,Upper}}$ and $\gamma_{\text{Th,Lower}}$. In order to adjust the transmission power level optimally during data communication, receiving node sends the current RSSI value in a notification message to the transmitting node only when if the RSSI crosses the RSSI region. Upon receiving the notification, transmitter adjusts the transmission power level according to the current RSSI value in order to keep the RSSI inside the selected RSSI region. However, if the RSSI value is within the RSSI region i.e., between the threshold levels, $\gamma_{\text{Th,Upper}}$ and $\gamma_{\text{Th,Lower}}$, receiver will not send the notification message and thus, the power controller at the transmitter will not adjust the transmission power level. This is not an energy efficient approach. Because if the RSSI value is just below the $\gamma_{\text{Th,Upper}}$ threshold level, there is still a possibility that we can achieve the same PRR with low transmission power level provided the RSSI value remains stay above the $\gamma_{\text{Th,Lower}}$ threshold level.

In Modified-ODTPC, a margin of say 10 dBm is set above the $\gamma_{\text{Th,Lower}}$. If the current RSSI value is within the RSSI region, even then the power level will be decreased up to a level at which the margin was set. In this way the transmitting node tries to bring the RSSI slightly above the $\gamma_{\text{Th,Lower}}$ threshold. This results in saving the energy of the transmitting node and thus, an overall increase in the lifetime of WSNs. During the data communication, average PRR must be kept in observation. Using MODTPC strategy, if the packet loss is high, this margin can be increased gradually. In contrast, if the 100% PRR is maintained, the margin window can be gradually decreased.

Table 3.1: Simulation Parameters

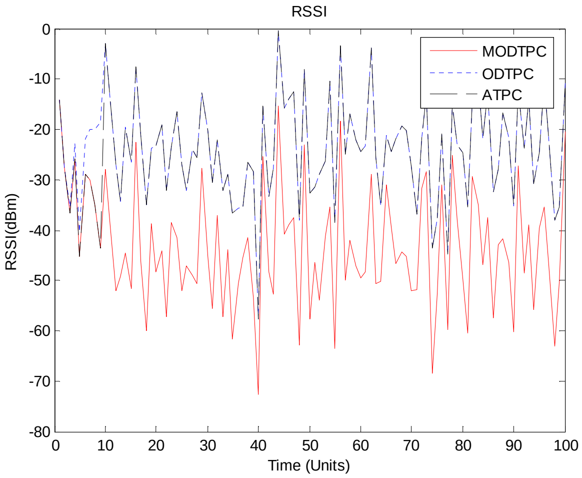
Simulation Parameters	**Values**
Transmission Power levels	31 to 3 (0 to -25 dBm)
Range of RSSI	0 to -100 dBm
Simulation Time	100 units
Distance between Tx and Rx	100 m
Noise Variance	16
Path loss Exponent	2.5
Carrier frequency	2.4 GHz

3.4 Simulations and Results

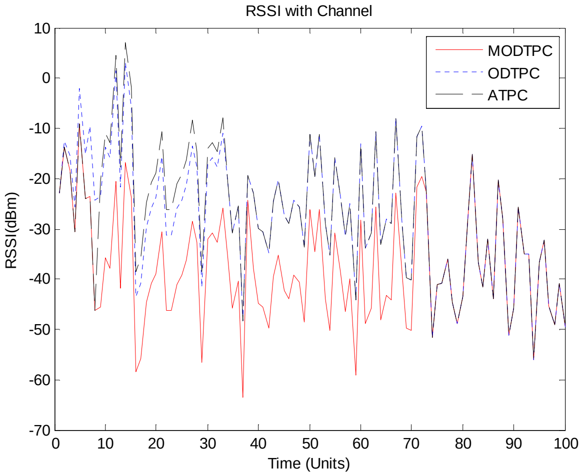
3.4.1 Simulation Setup

The performance of the proposed power controller algorithm, MODTPC, is evaluated by simulation. The simulator is Matlab®. The simulation parameters are listed in Table 3.1. The purpose of this section is to compare MODTPC with its predecessors, ATPC [65] and ODTPC [19], from different aspects. In order to present the comparison in an efficient way, the simulation is done with three different RSSI lower threshold levels: -50 dBm, -60 dBm and -70 dBm; while the RSSI upper threshold levels are fixed to 0 dBm, -10 dBm and -20 dBm.

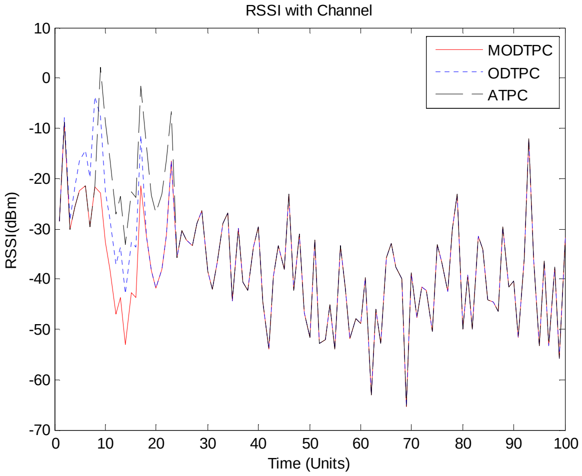
Fig.s 3.2(a), 3.2(b) and 3.2(c) show the RSSI of three power control algorithms: MODTPC, ATPC [65] and ODTPC [19]. As the proposed power controller, MODTPC, consumes less energy by keeping the transmission power level low as shown in Fig.s 3.3(a), 3.3(b) and 3.3(c) its RSSI is shown below than the other two algorithms in Fig.s 3.2(a), 3.2(b) and 3.2(c). This is a very good approach to use the power levels as low as possible provided the achieved RSSI is sufficient, acceptable and remains above the lower threshold level.



(a) $\gamma_{\mathrm{Th,Low}}$=-50 dBm, $\gamma_{\mathrm{Th,Upper}}$=0 dBm

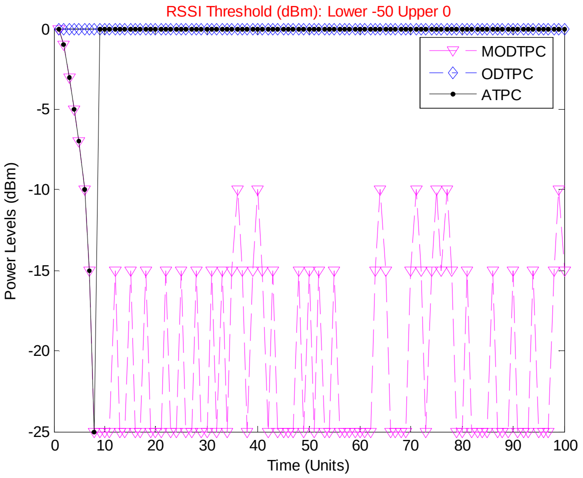


(b) $\gamma_{\mathrm{Th,Low}}$=-60 dBm, $\gamma_{\mathrm{Th,Upper}}$=-10 dBm

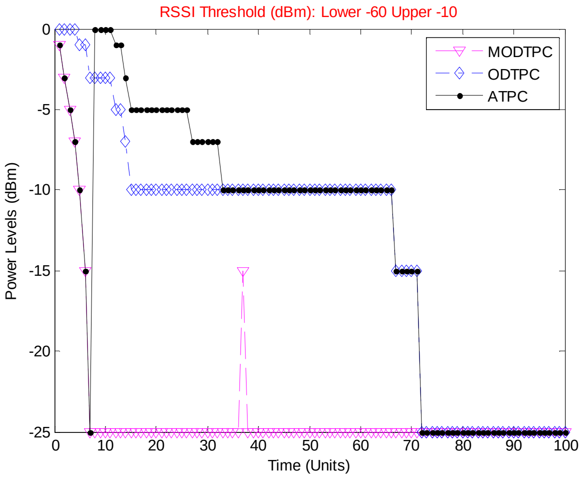


(c) $\gamma_{\mathrm{Th,Low}}$=-70 dBm, $\gamma_{\mathrm{Th,Upper}}$=-20 dBm

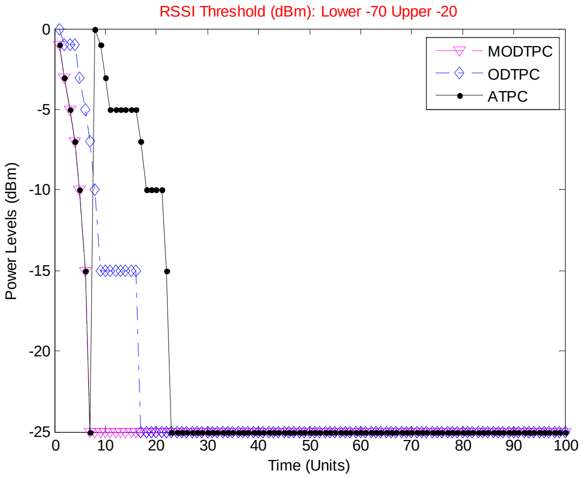
FIGURE 3.2: RSSI Behavior for MODTPC, ODTPC and ATPC Power Controllers



(a) $\gamma_{\mathrm{Th,Low}}$=-50 dBm, $\gamma_{\mathrm{Th,Upper}}$=0 dBm



(b) $\gamma_{\mathrm{Th,Low}}$=-60 dBm, $\gamma_{\mathrm{Th,Upper}}$=-10 dBm



(c) $\gamma_{\mathrm{Th,Low}}$=-70 dBm, $\gamma_{\mathrm{Th,Upper}}$=-20 dBm

FIGURE 3.3: Power Levels for MODTPC, ODTPC and ATPC Power Controllers

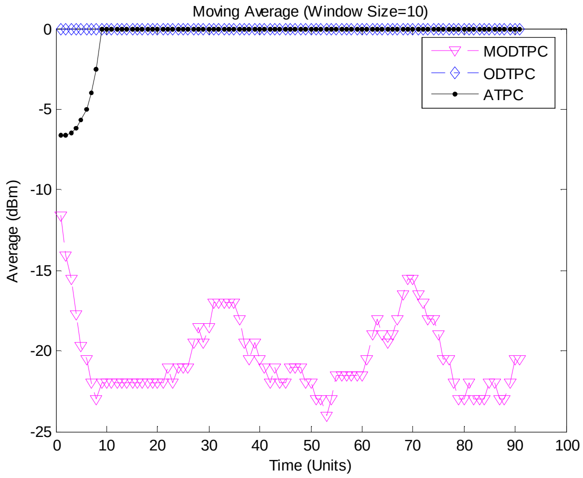
Fig.s 3.3(a), 3.3(b) and 3.3(c) show the transmission power adjustment levels at difference RSSI lower threshold levels. It is clear from the figure that proposed protocol uses less power than the other protocols considered for evaluation. This is due to the fact that the other two approaches, ODTPC [19] and ATPC [65], do not reduce the transmission power level when the received RSSI is within the RSSI region i.e., between lower and upper RSSI threshold levels. The case when RSSI is within the RSSI region occurs very frequently, due to which both ATPC [65] and ODTPC [19] do not reduce their power levels most of the time. This is the major drawback of using these approaches though reliable communication can be done at low power levels.

In addition, all the three approaches are compared on the basis of moving average and moving variance. These are used for the trend analysis of a curve. It focuses on the noticeable changes in a curve while ignores and avoid to show the minor changes in a curve. This results in better analysis of the behavior of a curve in an efficient manner. In Fig.s 3.4(a), 3.4(b) and 3.4(c), it is clear that ODTPC [19] and ATPC [65] are working on very high transmission power levels. In Fig.s 3.5(a), 3.5(b) and 3.5(c), moving variance describes the frequency of changing behavior of the transmission power levels. As the proposed approach is trying to keep at the lowest power level, its frequency of changing power levels is high as compared to other two strategies.

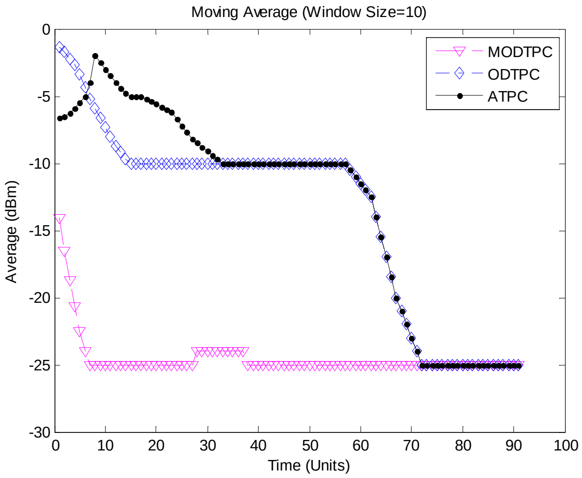
All the three power control approaches are compared with the help of efficiency plot. Thus, efficiency of each of the three power control strategies is evaluated. From the Fig.s 3.6(a), 3.6(b) and 3.6(c), it is clear that MODTPC is more efficient than ODTPC [19] and ATPC [65]. Efficiency can be modeled as:

$$\psi = \frac{\text{PRR } (\%)}{\text{Consumed Energy}(\text{mJ})} \qquad \textit{Eq (3.1)}$$

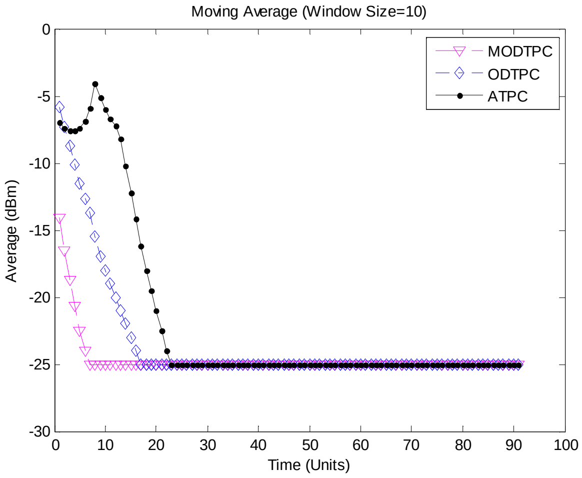
Finally, energy plots of all three power controllers are shown in Fig.s 3.7(a), 3.7(b) and 3.7(c). It is clear that MODTPC saves more energy than ODTPC [19] and



(a) $\gamma_{\mathrm{Th,Low}}$=-50 dBm, $\gamma_{\mathrm{Th,Upper}}$=0 dBm

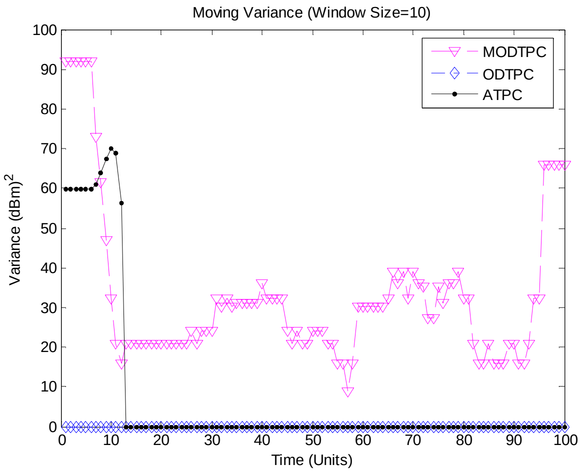


(b) $\gamma_{\mathrm{Th,Low}}$=-60 dBm, $\gamma_{\mathrm{Th,Upper}}$=-10 dBm

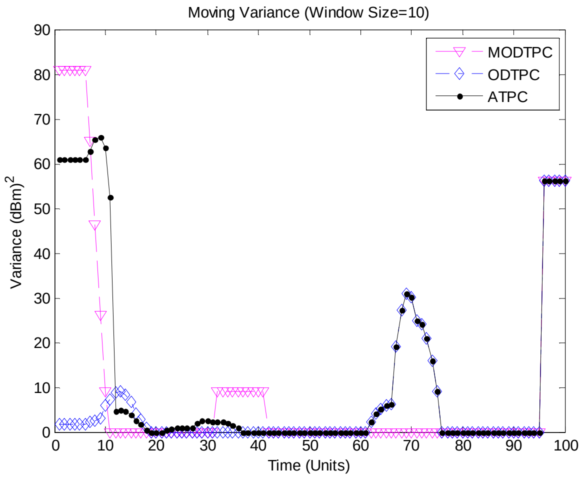


(c) $\gamma_{\mathrm{Th,Low}}$=-70 dBm, $\gamma_{\mathrm{Th,Upper}}$=-20 dBm

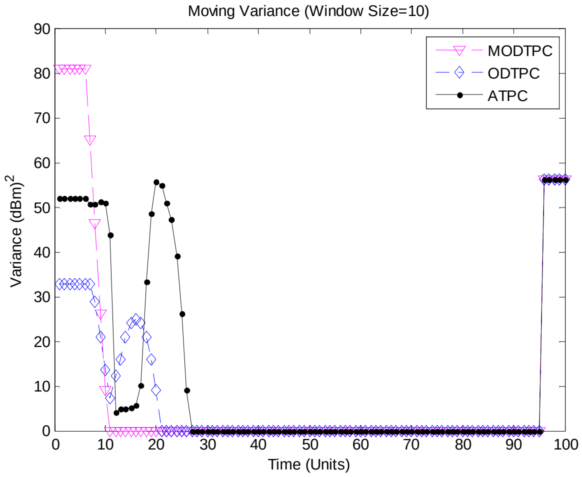
FIGURE 3.4: Moving Average of MODTPC, ODTPC and ATPC Power Controllers



(a) $\gamma_{\mathrm{Th,Low}}$=-50 dBm, $\gamma_{\mathrm{Th,Upper}}$=0 dBm

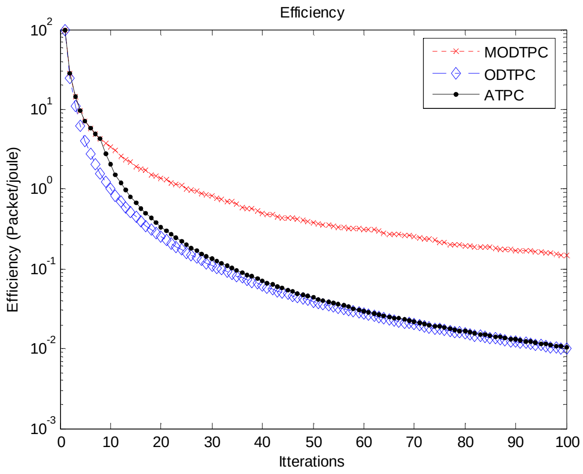


(b) $\gamma_{\mathrm{Th,Low}}$=-60 dBm, $\gamma_{\mathrm{Th,Upper}}$=-10 dBm

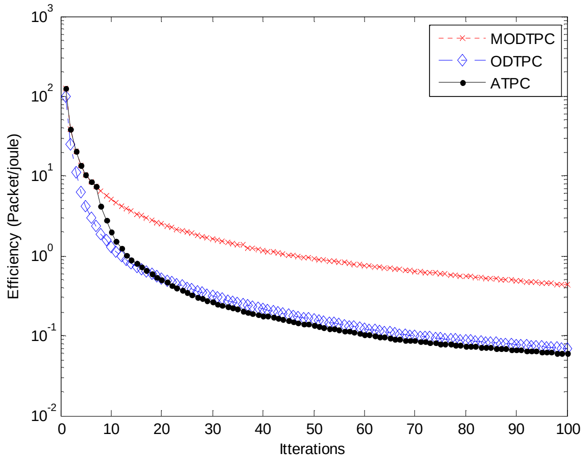


(c) $\gamma_{\mathrm{Th,Low}}$=-70 dBm, $\gamma_{\mathrm{Th,Upper}}$=-20 dBm

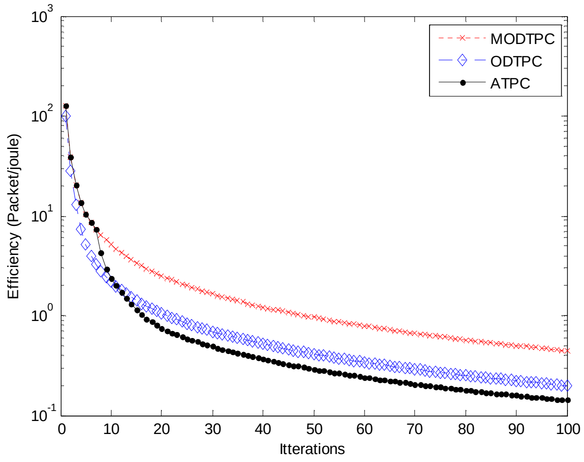
FIGURE 3.5: Moving Variance of MODTPC, ODTPC and ATPC Power Controllers



(a) $\gamma_{\mathrm{Th,Low}}$=-50 dBm, $\gamma_{\mathrm{Th,Upper}}$=0 dBm

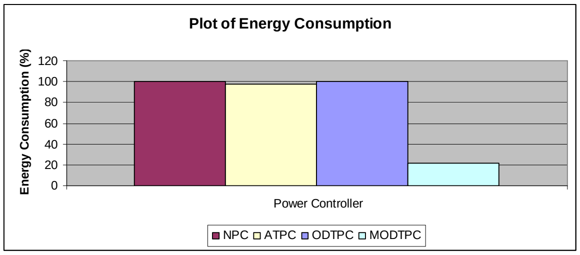


(b) $\gamma_{\mathrm{Th,Low}}$=-60 dBm, $\gamma_{\mathrm{Th,Upper}}$=-10 dBm

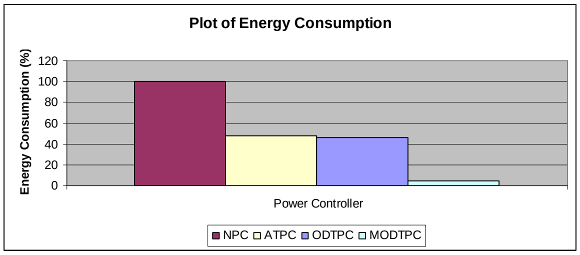


(c) $\gamma_{\mathrm{Th,Low}}$=-70 dBm, $\gamma_{\mathrm{Th,Upper}}$=-20 dBm

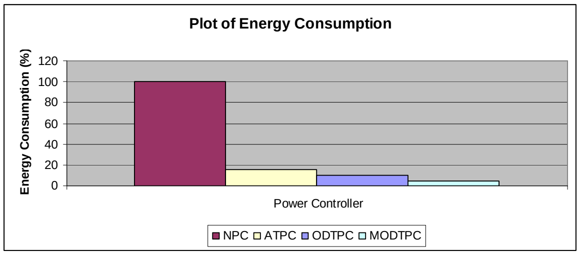
FIGURE 3.6: Efficiency of MODTPC, ODTPC and ATPC Power Controllers



(a) $\gamma_{\text{Th,Low}}$=-50 dBm, $\gamma_{\text{Th,Upper}}$=0 dBm



(b) $\gamma_{\text{Th,Low}}$=-60 dBm, $\gamma_{\text{Th,Upper}}$=-10 dBm



(c) $\gamma_{\text{Th,Low}}$=-70 dBm, $\gamma_{\text{Th,Upper}}$=-20 dBm

FIGURE 3.7: Energy Consumption of MODTPC, ODTPC and ATPC Power Controllers

ATPC [65] especially in the case when RSSI remains within the RSSI region. Here, NPC (No Power Control) uses the max power level.

3.5 Experimental Evaluation of TPC Protocols

3.5.1 Experimental Setup

In this section, performance analysis of three well known transmission power control algorithms in wireless sensor network is presented using Sun SPOT® (Small Programmable Object Technology) [66] test bed. Various plots presented in this section are obtained through multiple runs of these algorithms on the test bed. Experimental parameters are listed in Table 3.2.

The unique features of MODTPC which distinguishes it from other TPC approaches is that it tries to adjust the transmission power level as low as possible. Sun SPOT® [66] that uses CC2420 [16] radio is tested for various RSSI levels and assures 95% PRR up to -85 dBm RSSI as shown in Fig. 3.8. In MODTPC, the power controller algorithm forces the RSSI to stay near the lower threshold in order to save energy; therefore in the case of MODTPC, RSSI frequently crosses the lower threshold which may result in poor PRR. In order to improve the PRR, a margin line above the lower threshold may be set to -75dBm which can also be changed, depending on the current PRR. The RSSI behavior using NPC (No Power Control), ODTPC [19], ATPC [65] and MODTPC is shown in Fig. 3.9. The relative transmission power control of these TPC strategies is shown in Fig. 3.10 which shows whether the change in power level is swift or gradual. ATPC has

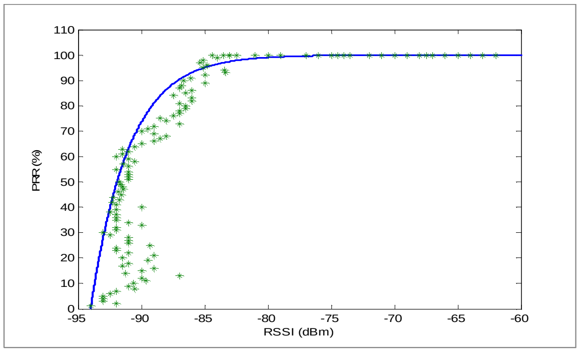


Figure 3.8: PRR Vs. RSSI

Table 3.2: Experimental Parameters

Experimental Parameters	**Values**
Transmission Power levels	31 (0dBm) to 3 (-25dBm)
RSSI Normal Range, γ	0 to -100 dBm
γ_{Lower}	-84 dBm
Path loss Exponent	2.5
Carrier Frequency	2.4 GHz

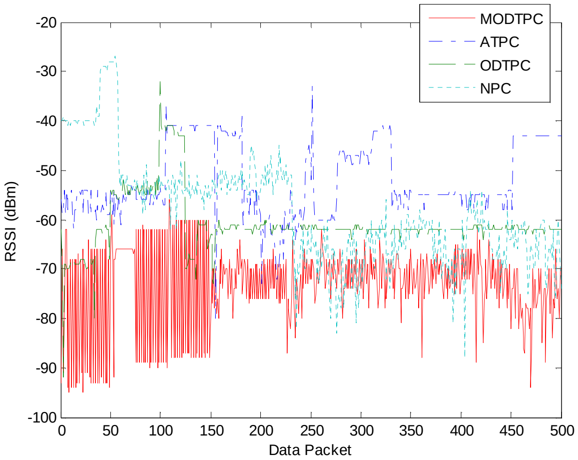


Figure 3.9: RSSI Behavior using NPC, ATPC, MODTPC and ODTPC

the ability to change transmission power swiftly which makes it less vulnerable to packet loss, while the ODTPC [19] and MODTPC change the power levels at a rate of one step at a time.

While analyzing the performance of the power control algorithms the overall energy saving acts as one of the most important parameters. A pre-defined set of packets are transmitted using ODTPC [19], ATPC [65], MODTPC and NPC mechanism under similar circumstances and their power consumption is evaluated. Fig. 3.11 shows that the battery consumption of ODTPC [19], ATPC [65], MODTPC and NPC. NPC no doubt consumes much more energy as compared to the three power control strategies. MODTPC outperforms ATPC and ODTPC in terms of energy saving which makes MODTPC the optimum choice for the applications where the node energy is the most critical constraint.

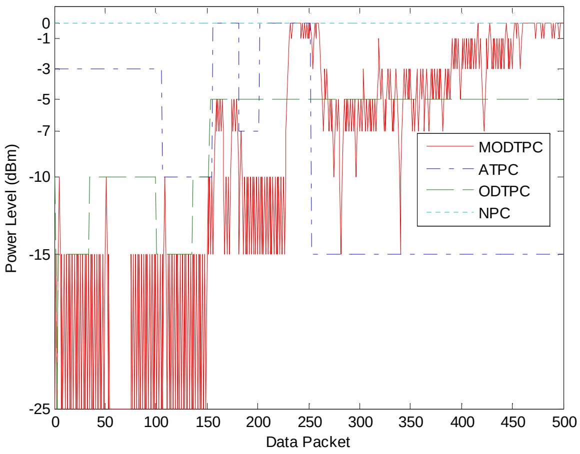


FIGURE 3.10: Transmission Power Adjustment using ODTPC, MODTPC, ATPC and NPC

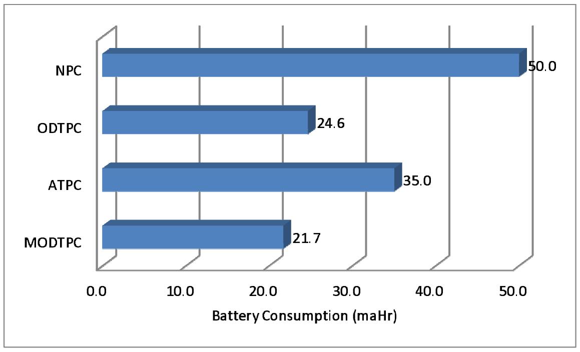


FIGURE 3.11: Overall Battery Consumption of a Node

3.6 Conclusion

Transmission power control is a way to reduce the energy consumption in WSNs. Many existing works on TPC have presented in literature. In this chapter, a modified version of ODTPC named MODTPC is proposed. MODTPC dramatically reduces the energy consumption as compared to ODTPC [19] and ATPC [65]. It is clear from the simulation and experimental results that MODTPC performs better in terms of energy saving than its predecessors ODTPC [19] and ATPC [65].

Chapter 4

ADAPTIVE POWER CONTROL-BASED ENERGY EFFICIENT ROUTING (APCEER) IN WIRELESS SENSOR NETWORKS

4.1 Introduction

4.1.1 Overview

In order to deliver sensed data to the sink reliably over an error prone wireless channel with less energy consumption, there is a need of an energy efficient routing protocol. As discussed in Chapter 3, there are numerous ways to achieve this goal out of which transmission power control (TPC) is a key technique. TPC is used to reduce radio interference, increase network connectivity and prolong network lifetime. In this chapter, TPC strategy is exploited in routing data from source to sink while utilizing the minimum required power. In our proposed strategy, an optimized transmission power level of any individual sensor node with its neighbor nodes is estimated adaptively. This results in huge power saving as compared to existing traditional routing protocols where only maximum transmission power level is used for radio communication.

4.1.2 Related Work

A significant work has already been done in order to achieve desirable reliability and improve network lifetime in wireless sensor networks. A tradeoff between these goals can only be made through the efficient utilization of network energy.

Some of the existing work on routing protocols and transmission power control strategies have already been discussed in Chapter 2 and Chapter 3 respectively. In this chapter, some more existing routing strategies and transmission power control approaches are going to be discussed.

A node can communicate with the sink in one of two ways: direct communication with the sink or indirect communication with the sink. It has been noticed that direct communication between a node and sink enjoys shortest communication time but it consumes high energy. Therefore, most of the routing protocols use indirect communication technique i.e. multihop routing. In multihop routing, shortest path or minimum-hop routing is used in order to reach the destination in least possible time. Examples are [29] and [67]. However, in such routing strategies shortest routing paths are used very frequently which results in quick energy depletion of low power nodes along the shortest path. This also results in disconnected networks.

Routing protocols in wireless sensor networks can be divided into two main categories: proactive and reactive. Proactive routing collects the routing information and creates routing tables at each sensor node prior to data communication. It appears to be an overhead, but results in a quick route discovery. In contrast, routes are discovered at runtime in reactive routing protocols. DSDV [29] and AODV [30] are the good examples of proactive and reactive routing protocols respectively.

There are certain power aware routing strategies like Power-Aware Routing (PAR) [68] in which least power cost routes are selected. However, in such schemes it is possible that a short residual-energy node that is selected multiple times, suffers from quick energy depletion. This leaves the network unstable and disconnected.

In order to make the network stable, another routing strategy the Lifetime Prediction Routing (LPR) [69] that uses battery lifetime prediction is proposed. It chooses a routing path whose lifetime is maximum. The lifetime of the network is predicted on the basis of the minimum lifetime value of any node along a particular path. Thus, the path having maximum of the calculated minimum lifetime values is selected. Although it results in a more stable network, it suffers from high routing cost.

In Cost Effective Maximum Lifetime Routing (CMLR) technique [70], a tradeoff between network lifetime and power awareness is maintained in order to achieve a more stable network than LPR [69] and require less routing cost than PAR [68]. CMLR [70] is based on a path selecting parameter, β, that is equal to the ratio of minimum lifetime among all the nodes along the path and the sum of all the costs calculated between two consecutive nodes along the path. A path with largest β is selected as a routing path. Although CMLR maintains a good tradeoff between network lifetime and power awareness, there are instances where it fails to produce correct results.

There are some geographical routing protocols which require the location of the neighboring nodes and sink at each node [71]. This is done by exchanging location information of every sensor node with all of its neighboring nodes. A node sends data to its particular neighbor node which is closest to the sink node. Location of a node can be collected by GPS or by running any localization algorithm. Use of GPS are not recommended due to two reasons [41]: Firstly, GPS receivers do not work inside buildings. Secondly, it is too costly to install GPS with every sensor node. Use of localization algorithms is an overhead but is a better solution for geographical routing protocols.

A major bottleneck of WSN performance is the limited energy of sensor nodes in the vicinity of sink. The nodes near the sink are heavily utilized due to their critical positions. In order to minimize the energy consumption of these nodes and to evenly distribute the load, mobile sink can be used where new sensor nodes become sink's neighbors on the movement of the sink to a new location. Local Update-based Routing Protocol (LURP) [51] works on the same principle. In LURP, sink node broadcasts its location information to only a small number of nodes that reside within a local area. A node considers another node from where it receives the sink's location as a next hop node. Only when the sink moves outside this local area, the location information propagates throughout the network. The disadvantage of using mobile nodes is that they need complex procedure to control and manage their own operations. In addition, these can only be used in applications where deployment area is accessible to mobile nodes [5] and hence, LURP works in only those application areas where sink mobility is allowed.

Hierarchical routing protocols use another way to route data from source to sink in which network is divided into clusters [71]. Each cluster is managed by a Cluster Head (CH) which collects data from cluster members and send it to sink or neighbor cluster head. In this way, all nodes within a cluster are only concerned with communicating to their cluster heads. Cluster heads then communicate to sink directly or indirectly via other cluster heads. CHs are either homogeneous [39] [53] [72] or heterogenous [73] [74] in nature with the normal sensor nodes. In case if CHs are heterogenous, they are more powerful in terms of energy, processing capability and memory than the normal sensor nodes. One of the major benefit of this strategy is data aggregation or fusion in which redundant data is removed at the cluster head. This saves energy as redundant data is not transmitted towards sink. However, this saving can only be achieved in communication between CH and sink. Applications where data is continuously transmitted with high redundancy from source to sink, hierarchical routing is most suitable. Examples of such routing schemes are LEACH (Low Energy Adaptive Clustering Hierarchy) [39] , PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [53], LEACH-C [24] and TEEN (Threshold Sensitive Energy Efficient Sensor Network Protocol) [54].

As stated earlier, energy is the most critical resource of a sensor node. The batteries of these unattended sensor devices are usually not rechargeable. Therefore, there is a need of a routing mechanism which selects routing paths according to energy factor and utilizes each sensor node in the sensor network in an energy efficient manner. During the last decade, many energy-aware routing protocols have been proposed [28] [61] [75]; some of these have been discussed in Chapter 2. A detailed survey on these and other routing protocols of WSN has been carried out in [52]. Shah *et al.* [75] proposed an energy-aware routing protocol in which suboptimal, in addition to optimal, routing paths are selected in order to prolong the network lifetime. Authors pointed out that using minimum energy paths all the time results in the energy depletion of nodes on that path. Khalid *et al.* [61] proposed an energy efficient routing protocol to route real-time data from source to sink, introducing the concept of vulnerability of nodes in a network.

There are some gradient-based routing protocols like GRAB (GRAdient Broadcast) [28], GBR (Gradient Based Routing) [76] and GRACE (GRAdient Cost-field Establishment; proposed in Chapter 2). In GBR [76], each node maintains a variable known as height of the node in which the current number of hops from the respective node to the sink stored. The difference between the heights of a node and of its neighbor is calculated, as a gradient. The node selects the largest gradient to reach the sink. As discussed in Chapter 2, GRAB [28] is another gradient-based routing protocol, in which cost to reach the sink is maintained at each node. A node broadcasts the data along with its own cost and only the nodes having lower costs than the sender forward the data towards sink. GRACE, proposed in Chapter 2, differs with GRAB in a way that each node does not broadcast data packets. It selects the least cost neighbor to forward data towards sink. The key feature of GRACE is the different modes for updating status information at each sensor node. Using these modes, up-to-date status information can be maintained at each node easily without any congestion and extra overhead. The performance of GRACE is better than GRAB in terms of network lifetime and energy consumption.

A modified version of GRAB is proposed in [77], where in order to update the cost field at each sensor node, different modes for updating status information are used. Use of these modes enhances the overall efficiency of GRAB.

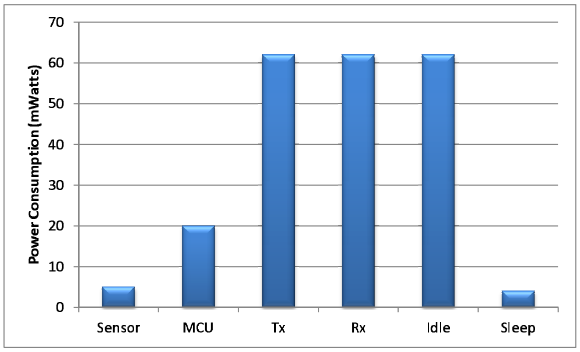


FIGURE 4.1: Power Consumption of MicaZ

Power consumption in a WSN is due to three basic operations: sensing, processing and communication. It has been noted that communication that includes transmission and reception of data is more expensive in terms of battery power than sensing and processing. Fig. 4.1 shows the power consumption in mWatts by different units of a MicaZ sensor node. Here, MCU stands for power consumption by micro controller unit, while power consumption by radio unit includes power consumption in transmitting (Tx), receiving (Rx) and idle state [78]. Pottie et al. [3] state that battery consumed in processing 3000 instructions is equivalent to transmitting one bit of information over 100m. Therefore, there is a need to transmit intelligently in order to save the battery. One way of intelligent transmission is to control the transmission power. Current radios have the capability of adjusting its transmission power level, for example, CC2420 [16] has eight different transmission power levels which can be adjusted as per requirement. Most of the routing protocols do not consider this facility of a radio and transmit data with maximum transmission power level [28, 40, 50, 61]. This is also due to the fact that reliability and throughput are the major goals of conventional routing protocols and a misconception that these goals can only be achieved through the use of maximum transmission power level drives the basic concept of these protocols. However, the use of various transmission power control strategy has also been reported in the field [65] [19].

Kubisch et al. [79] presented two connectivity-base algorithms: LMA (Local Mean Algorithm) and LMN (Local Mean Neighbor). Both algorithms are supposed to ensure network connectivity by adjusting the transmission power level in such a way that a specific number of neighbors or the neighbors of neighbors of a transmitting node is acquired. This number is kept between two predefined thresholds. However, for LMA, this number is the number of the neighbors of the transmitting node, while for LMN, it is the number of the neighbors of the neighbors of the transmitting node. Nevertheless, these algorithms seem to fail in dynamic network conditions where the topology of the network changes rapidly, generating a frequent need of the information about the neighboring nodes. Such conditions, for example, can occur in a wireless sensor network. The frequency of the information gathering mechanism about the number of neighbors results in corresponding amount of energy overhead.

L. H. A. Correia *et al.* [80] proposed a transmission power control technique named Hybrid. In hybrid, each node determines an optimal power level by transmitting query packets at different power levels. Power adjustment is based on acknowledgements received from the receiving nodes. This algorithm thus focuses on maintaining connectivity and controlling topology.

As discussed in Chapter 3, in PCBL algorithm [64], an initialization phase runs after a specific period of time. This phase determines an optimum power level that ensures 100% Packet Reception Rate (PRR). Adaptive transmission power control (ATPC) algorithm [65] also uses an initialization phase before starting the data transmission phase in order to find an optimum power level. However, being different from PCBL, the optimizing parameters used are Link Quality Indicator (LQI) and received radio signal strength indicator (RSSI). Power adjustment at the transmitter is done according to a notification received from the receiving nodes if RSSI values crosses some predefined upper and lower threshold levels. Both PCBL [64] and ATPC [65] have initialization phase overheads which depend upon the frequency of initialization and become significant in case of channel fading. In addition, when channel state changes abruptly, there is no mechanism to adjust the power to the new optimal level directly and the link performance either severely degrades or results in wastage of extra energy.

In contrast, ODTPC [19] does not use an initialization phase. Whenever transmitter needs to transmit data to any of its neighbors, it sends its first data packet with maximum transmission power. Upon receiving the first data packet, the receiver informs the transmitter if the RSSI is above or below a certain threshold region. Since, ODTPC [19] does not need the initialization phase as compared to ATPC [65], therefore, less energy is consumed in ODTPC [19]. However, getting the correct transmission power level in ODTPC [19] will take time as it increases or decreases its transmission power level in fixed steps. For example in case if the RSSI is very low due to severe loss in communication channel, the recovery process is not too fast as the power level increases with a fixed step size.

A common drawback of PCBL [64], ATPC [65] and ODTPC [19] is discussed in Chapter 3. In these TPC strategies, when the measured RSSI is within a threshold region, it will remain steady at a particular power level i.e. the system will not adjust (increase or decrease) its transmission power level. Although it seems to be good, yet it results unnecessary wastage of energy as the measured RSSI is usually much above the lower threshold level. Therefore, in real life, traditional power control strategies are not very functional in terms of energy saving due to the very uncertain behavior of the propagation environment. Thus an effective, optimal and adaptive power control strategy is required, if the sensor network resides in such a dynamic fading environment.

In [81], Huang *et al.* used Markov chains for transmission power control. In [21], Ares *et al.* presented two power control algorithms: Multiplicative-increase Additive-Decrease power control (MIAD-PC) and Packet Error Rate Power Control (PER-PC). PER-PC sets the transmission power level based upon the signal to inference plus noise ratio (SINR), while MIAD-PC is based upon the packet reception rate

(PRR). However, both of the models are not capable of working in dynamic fading environment

Quevedo *et al.* discussed the best possible channel state estimation strategy in [82], in which sink acts as a controller being capable of modifying the transmission power level of any sensor node. Thus, sensors are commanded by a sink to wake up, send data at a particular power level and then sleep.

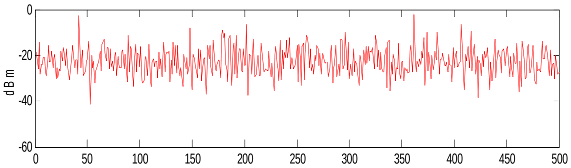
From the above discussion, it is concluded that transmission power control strategy utilizes the whole network in an energy efficient manner. It also deals with the dynamic nature of the channel which changes due to various environmental factors like fading and shadowing. RSSI shows the behavior of the channel at a particular instant of time. In the absence of any channel impairment like terrain and clutter, RSSI is more stable than if these effects are present. Fig. 4.2 shows the RSSI with and without channel impairments.

Thus, there is a need to adjust the transmission power adaptively as per need. In situations, where the channel is faded, high transmission power should be used to transmit data reliably. However, there is no need to transmit with maximum power when the channel is favorable. The strategy proposed in this chapter, Adaptive Power Control-based Energy Efficient Routing (APCEER), works on the same principle. It adjusts the transmission power adaptively in order to increase reliability and throughput while prolonging the network lifetime.

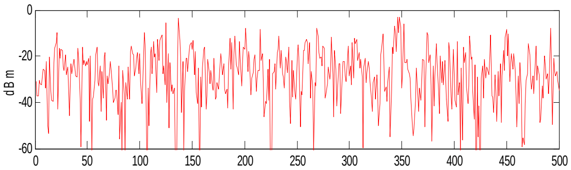
4.1.3 Problem Statement and Contribution

Although all of the discussed strategies work fine in an ideal environment; however, they are prone to undetectable errors, unpredictable failures and ineffective power exertion in harsh propagation environment due to various fading effects, external noises and disturbances.

As most of the routing strategies use maximum transmission power level for radio communication that reduces the network lifetime drastically. Therefore, there is a



(a) RSSI without Channel Impairments



(b) RSSI with Channel Impairments

FIGURE 4.2: Effect of Channel Impairment on RSSI

need of a such routing approach that uses minimum possible transmission power level while giving optimized and reliable throughput. Thus, the focus of this work is to achieve the mentioned goal through adaptively setting transmission power according to realistic propagation condition.

4.2 System Model

In this section, we present the various components of the system model for the proposed routing strategy, APCEER.

4.2.1 General Architecture

Before going into the details of APCEER, we, once again, refer to Fig. 1.1, where a general architecture of wireless sensor networks is shown. In this figure, one of the node acts as a source node which transmits its data to its neighboring nodes in order to convey the information to the sink, utilizing minimum possible transmission power level. The sink node then forwards data to a control center via satellite or internet for onward processing. The communication among these sensor nodes is made in a multi-hop fashion where a node acts as a sensor as well as a relay. A typical routing model used in wireless sensor networks is shown in Fig. 4.3. As discussed earlier in section 1.1, energy is a critical resource of a sensor

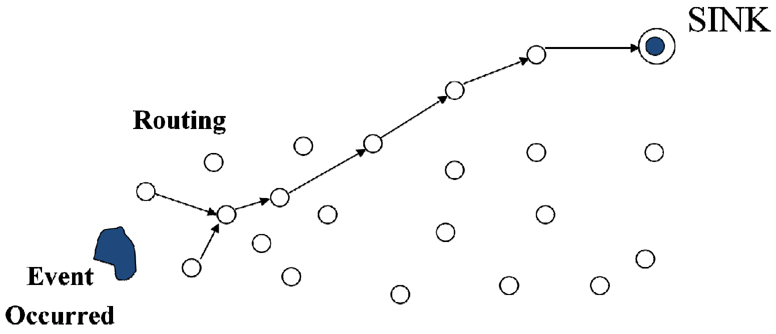


Figure 4.3: Routing Model

node in a wireless sensor network; therefore, optimal power utilization is needed. Thus, the goal of the proposed work is to find optimal path and to utilize energy as low as possible using transmission power control strategy in order to deliver data from one node to the other. This strategy achieves significant energy saving and hence, prolongs network lifetime.

4.2.2 Transmitter Model

Energy consumption in transmission of data is due to the following components [78]:

- Frequency Synthesizer
- Voltage-Controlled Oscillator (VCO)
- Modulator
- Power Amplifier (PA)

Here, the power consumed by modulator is negligible and hence, not considered. Thus, the energy consumed in transmission, E_{Tx}, is given by

$$E_{\mathrm{Tx}} = (P_{\mathrm{LO}} + P_{\mathrm{PA}})t_{\mathrm{Tx}} \qquad \textit{Eq (4.1)}$$

Where, P_{LO} is the power consumed by Frequency Synthesizer and VCO. t_{Tx} is the transmit duration (the time it takes to transmit). P_{PA} is the power consumed by the PA and depends upon the RF output power, P_{Out}. The relationship can be given by the following equation

$$P_{\mathrm{PA}} = \frac{1}{\eta_{\mathrm{Pow}}} P_{\mathrm{Out}} \qquad \textit{Eq (4.2)}$$

Where, η_{Pow} is the power efficiency of the power amplifier.
P_{Out}, a distance-dependent component, can be defined as

$$P_{\mathrm{Out}} = \gamma_{\mathrm{PA}}.R_b.d^n \qquad \textit{Eq (4.3)}$$

Where, R_b is the data rate, n is the path loss exponent that varies with respect to the propagation environment and γ_{PA} is a factor that depends upon the antenna gain, wavelength, thermal noise power spectral density and the desired SNR at distance d.
Finally, the energy consumption by the transmitter depends upon the rate at which data is transmitted. In the proposed routing protocol, an event-based routing mechanism is used where the data is communicated only when an event occurs. This rate is increased by sending control information among neighbors to collect neighborhood information. Thus, overall energy consumption can be modeled as

$$E_{\text{con-Tx}} = \sum_{i=1}^{N_{\mathrm{Tx}}} [P_{\mathrm{LO}}(t_{\mathrm{Tx},i} + t_{\mathrm{startup}}) + P_{\mathrm{PA},i}(t_{\mathrm{Tx},i})] \qquad \textit{Eq (4.4)}$$

Where, $P_{\mathrm{PA},i}$ is the power consumed by the PA for the i^{th} transmit interval transmitting at a specific power level, P_{Out}; $t_{\mathrm{Tx},i}$ denotes the i^{th} transmit duration, N_{Tx} is the number of times transmitter is switched on and t_{startup} is the constant startup time for the local oscillator to get prepared for transmission.

4.2.3 Channel Model

The signal transmitted by a transmitting node travels through a fading propagation environment. The characteristics of the fading environment distort the signal in both amplitude and phase which in turn causes the loss of information. The faded signal possesses the information of the fading channel and helps to understand the characteristics of the environment.
Rayleigh fading channel distribution is assumed to model the multi-path time-varying fading process. Rayleigh fading process can be visualized with an autoregressivemoving-average (ARMA) model as

$$h(k) = \alpha h(k-1) + \omega(k-1) \qquad \textit{Eq (4.5)}$$

where $\omega(k-1)$ is a Gaussian distributed zero mean i.i.d. process with variance Q_ω, α being channel autocorrelation function accounts for the channel Doppler spread and can be set as $J_0(2\pi f_d T_s)$ where $J_0(.)$ is a zeroth order Bessel function, f_d is the Doppler frequency and T_s accounts for the time lag of two consecutive channel states usually taken as a symbol period [83] [84].

4.2.4 Receiver Model

4.2.4.1 Receiver Energy Consumption

Energy consumption in reception of data by the receiver is due to the following components [78]:

- Frequency Synthesizer
- Voltage-Controlled Oscillator (VCO)
- Mixer
- Low Noise Amplifier

- Intermediate Frequency Amplifier
- Demodulator Components

The energy consumption by the receiver is represented by following equation

$$E_{\mathrm{Rx}} = (P_{\mathrm{LO}} + P_{\mathrm{Rx}})t_{\mathrm{Rx}} \qquad \textit{Eq (4.6)}$$

Where, P_{LO} is the power consumed by Frequency Synthesizer, P_{Rx} is the power dissipated by rest of the components and t_{Rx} is the receiving duration (the time it takes to receive).
Overall energy consumption is based upon the rate at which data is received. Thus, the overall energy consumption is given by

$$E_{\text{con-Rx}} = \sum_{i=1}^{N_{\mathrm{Rx}}}[(P_{\mathrm{LO}} + P_{\mathrm{Rx}})(t_{\mathrm{Rx},i} + t_{\mathrm{startup}})] \qquad \textit{Eq (4.7)}$$

Where, $t_{\mathrm{Rx},i}$ denotes the i^{th} receiving duration, t_{startup} is the constant startup time for the receiver and N_{Rx} is the total number of times, the receiver is turned on.

4.2.4.2 Receiving (RSSI) Model

Theoretical and measurement-based models in the literature indicate that the received signal power decreases logarithmically with respect to distance [85]. Therefore, it is obvious to represent received signal power as a function of distance. Large-scale path loss model together with the clutter noise results in a log-normal shadowing path loss model and has been used to model received signal power [86]. It is often considered to model and analyze received signal strength indicator (RSSI) without the involvement of channel attenuations. However, this is quite evident that the propagation medium between the transmitter and receiver is always disturbed by the fading environment, which produces fluctuations in the

RSSI values. The received signal strength indicator (RSSI) also becomes a random and stochastic phenomenon when uncertainty of multipath signals scattering by moving objects or received at moving receiver is added up to a fixed value that is dependant only on the separation between transmitter and receiver. Since, RSSI is composed with the channel impairments inherently, therefore, it is needed to deal RSSI with the involvement of channel impairments. The received signal power or RSSI at the distance d can be formulated as

$$\gamma = \gamma_0 + 10n\log(\frac{d_0}{d}) + X_\sigma \qquad \textit{Eq (4.8)}$$

Where

d_0 = close − in − reference distance from the transmitting node to a point in the close proximity of the node

γ_0 = received signal power at close − in − reference distance, d_0

d = transmitter − receiver separation

n = path loss exponent, dependent upon the propagation environment, varying from 2 to 6

X_σ = uncertainty in the received power in dB due to any unknown random sources. This uncertainty is usually modeled as zero − mean Gaussian i.i.d. process with standard deviation, σ

4.2.5 Routing Model

The cost field at each sensor node can be defined in terms of hop count, energy consumption and/or delay etc. In this chapter, it is defined in terms of energy of the nodes in a route and the quality of the links between transmitting and the last receiving node. Our routing model is based on the concept of gradient cost field establishment, GRACE, proposed in Chapter 2. The concept of gradient cost field establishment is taken from the natural phenomenon where water comes down from the top to the bottom of a valley. Similarly, the data propagates in a direction where it finds a path of minimum cost. Below is the detailed description of gradient cost field establishment and the factors it is based upon.

4.2.5.1 Energy Cost of $i^{\mathbf{th}}$ Node, $\mathbf{C}_{\mathbf{E},i}$

Energy cost of an i^{th} node, $\mathrm{C}_{\mathrm{E},i}$, is the same as given in equation (2.1) i.e.,

$$\mathrm{C}_{\mathrm{E},i} = \frac{\mathrm{E}_i^0}{\mathrm{E}_i} \qquad \textit{Eq (4.9)}$$

where, E_i^0 is the starting battery power of i^{th} node and E_i is the remaining battery power of i^{th} node.

4.2.5.2 Link Cost, $\mathbf{C}_{\mathbf{L},u\to v}$

Link cost between transmitting node u and receiving node v, $\mathrm{C}_{\mathrm{L},u\to v}$, is also the same as given in equation (2.2) i.e.,

$$\mathrm{C}_{\mathrm{L},u\to v} = \frac{P_{\mathrm{t},u}}{P_{\mathrm{r},v}} \qquad \textit{Eq (4.10)}$$

where, $P_{\mathrm{t},u}$ is the transmitted power of node u and $P_{\mathrm{r},v}$ is the received power of node v.

4.2.5.3 Route Cost, $\mathbf{C}_{N_1\to N_2}$

Route cost between the path-starting node N_1 and the path-terminating node N_2 is given by

$$\mathrm{C}_{N_1\to N_2} = \sum_{i=N_1}^{N_2-1} (\Omega_E \mathrm{C}_{\mathrm{E},i} + \Omega_L \mathrm{C}_{\mathrm{L},i\to i+1}) \qquad \textit{Eq (4.11)}$$

where, Ω_E and Ω_L represent the weighting factors of energy and link costs respectively. In our case, take Ω_E as 0.999 and Ω_L as 0.0001 . Since the values of

Ω_E and Ω_L depend on battery quality and channel conditions, they can thus be measured or estimated specifically for the environment and nodes to be used in wireless sensor networks.

4.2.5.4 Important Definitions in Cost Establishment

Following are the useful definitions in cost field establishment:

α_I The advertisement information sent from node I to its neighboring nodes.

$C_{I \to S}$ The minimum-cost path from node I to sink S. This shows the only available minimum-cost path.

$C_{I \to J \to S}$ The path from node I to sink S utilizing node J in the routing path. This represents actually a single specific path originating from node I out of many available paths terminating at sink S.

TABLE 4.1: Power Levels

Transmit Power Level	RF Output Power(dBm)	Current Drawn (mA)
31	0	17.4
27	-1	16.5
23	-3	15.2
19	-5	13.9
15	-7	12.5
11	-10	11.2
7	-15	9.9
3	-25	8.5

4.3 Proposed Routing Strategy - Adaptive Power Control-based Energy Efficient Routing (APCEER)

4.3.1 General Assumptions

We make the following assumptions in the design of APCEER:

- All sensor nodes are assumed to be homogenous.
- All sensor nodes are deployed randomly and heavily to avoid network partitioning.
- At the beginning, transmission power of all sensor nodes are set to maximum.
- There is only one stationary sink and multiple stationary sources are present in the network.
- The source can be any node in the whole network.
- There are any number of relay nodes between a source and sink.

4.3.2 Basic Routing and Power Control Scheme of APCEER

APCEER is actually a routing protocol with transmission power control mechanism. There are two phases of APCEER: setup phase and data communication phase. In the following sections, these phases are explained in detail along with an example scenario.

4.3.2.1 Setup Phase

In setup phase, a cost field is established throughout the network. Initially at the sink node S, cost value is set to zero; while at all other nodes, cost value is set to infinite, ∞. After this initialization, each node (starting from the sink S) broadcasts as its advertisement information its cost to reach the sink through it with maximum transmission power. After receiving this advertisement information from all neighboring nodes, a node on one hand sets a suitable power level for each of its neighboring nodes based on their received signal strength indicator (RSSI) values for future transmissions and on the other hand, updates its cost to reach sink S by choosing the path of the minimum-cost neighbor. The power level information is stored in a routing table along with cost value at each node.

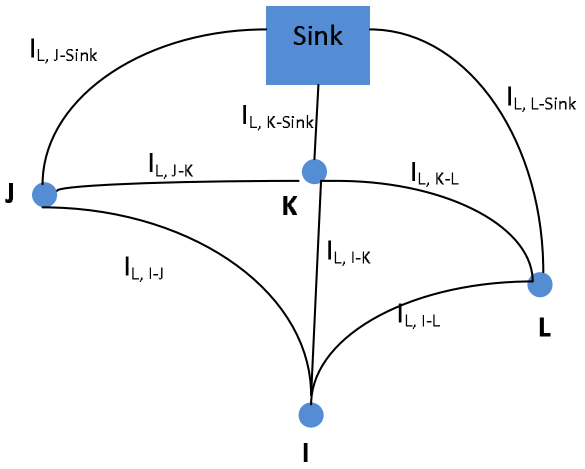


FIGURE 4.4: Cost Field Establishment

Available power levels along with corresponding current consumption for CC2420 radio [16] are listed in Table 4.1. A node broadcasts an advertisement information, α, which consists of the route cost from this node to the sink S. This cost at a node is formed by adding node's energy cost, $\mathrm{C}_{\mathrm{E,node}}$, to the cost of the selected minimum-cost neighbor out of all available neighbors. Later on, if a node receives again a new cost value from any of its neighbors, one of these two cases may exist: If the received cost value is greater than what the receiver broadcasted earlier, it will be ignored; however, if the received cost value is lesser than the earlier broadcasted value, receiver will replace the previous minimum-cost value with the newly-received cost value in its routing table and will rebroadcast it as its cost value to its neighbors. In this way, each node (starting from the sink side) in the network maintains a routing table. Fields of the routing table of a node contain IDs of its neighboring nodes, their corresponding cost values and transmission power levels, a flag value (either 1 or 0) which represents the minimum-cost neighbor (the selected neighbor), the selected cost value of the node, its energy cost $\mathrm{C}_{\mathrm{E,node}}$ and its advertisement information α_{node}. Thus, each node needs to maintain a least cost from itself to the sink S.

The cost field establishment can be better understandable by taking the example shown in Fig. 4.4 where nodes J, K and L are the immediate neighbors of the I^{th} node. We can define the cost fields and the advertisement information of the nodes as under:

$$\begin{aligned}
\alpha_{\text{J}} &= \text{C}_{J\rightarrow S} + \text{C}_{\text{E,J}} \\
\alpha_{\text{K}} &= \text{C}_{K\rightarrow S} + \text{C}_{\text{E,K}} \\
\alpha_{\text{L}} &= \text{C}_{L\rightarrow S} + \text{C}_{\text{E,L}} \\
\text{C}_{I\rightarrow J\rightarrow S} &= \alpha_{\text{J}} + \text{C}_{L,I\rightarrow J} \\
\text{C}_{I\rightarrow K\rightarrow S} &= \alpha_{\text{K}} + \text{C}_{L,I\rightarrow K} \\
\text{C}_{I\rightarrow L\rightarrow S} &= \alpha_{\text{L}} + \text{C}_{L,I\rightarrow L} \\
\text{C}_{I\rightarrow S} &= \min(\text{C}_{I\rightarrow J\rightarrow S}, \text{C}_{I\rightarrow K\rightarrow S}, \text{C}_{I\rightarrow L\rightarrow S})
\end{aligned}$$

Initially $\text{C}_{\text{node-Sink}}$ is set to infinity for all the nodes in the sensor field. The sink initiates the setup phase by broadcasting the advertisement information containing its cost as zero to all of its immediate neighbors J, K and L. Upon receiving the advertisement message with sink's cost, each node stores the cost in its routing table. Then it calculates the link cost $\text{C}_{\text{L,node-Sink}}$, as described in equation (4.10). Thus, each node's routing table contains cost $\text{C}_{Neighbor\rightarrow Sink}$ received from each of its immediate neighbors along with the neighbors' IDs. Now, the receiving node (say node 'I') assigns flag '1' to the neighbor with the smallest cost value (recorded as $\text{C}_{I\rightarrow Sink}$ in the table), calculates its own $\text{C}_{\text{E,I}}$ cost using equation (4.9) and records it in the routing table, $\text{C}_{\text{E,I}}$ is then added to $\text{C}_{I\rightarrow Sink}$ and the sum is broadcasted to all the immediate neighbors of node 'I' as its advertisement information, α_{I}. Also, the receiving node considers the minimum-cost node as the relay node to send data back to the sink. The similar algorithm runs on other nodes and this process continues till the last node of the sensor field gets its routing table. Once the setup phase is completed, the data communication phase is started to send data to the sink.

4.3.2.2 Data Communication Phase

Once the cost fields are established throughout the network in the setup phase, any node can send its data to the sink through the least-cost path. A source node sends data packet to its least-cost neighbor with its corresponding transmission power level indicated in the routing table. The cost values can be updated by using any of suggested modes of operation. These modes of operation for updating nodes' status information will be discussed in detail in section 4.3.2.4. During the routing of data packets, each node (source or relay) receives notification from the receiving node along with the acknowledgement if the RSSI crosses its predefined boundary upward or downward. The RSSI boundary is bounded with lower and upper threshold values which are set at the beginning of data communication phase. In addition, a margin line is drawn at a level of 10dBm above the lower threshold value i.e., if the lower threshold value is -80dBm, the margin line is set at -70dBm. Thus, if the RSSI goes down the margin line, receiver notifies the transmitter that there is a need of increasing transmission power level in order to ensure successful data reception. In contrast, if the RSSI is greater than the upper threshold value, the receiver notifies the transmitter that there is a need of decreasing the transmission power level in order to save the energy of the transmitting node and to decrease the interference to other nodes in the network. Upon receiving the notification from the receiving node, transmitting node either raises or drops the transmission power level by one step based upon the type of notification. Further data packets will be transmitted to the particular receiver with the new transmission power level. In case if there is no notification message received from the receiving node, transmitter still drops the transmission power level by one step until the power level touches the margin line.

4.3.2.3 A Backoff-based Cost Field Establishment

Using the setup phase discussed in Section 4.3.2.1, the number of broadcast messages that are exchanged among sensor nodes for cost field establishment is huge. This is due to the reason that whenever a node receives a cost value smaller than the previous broadcasted value, it retransmits or rebroadcasts the newly-received minimum cost value. Sometimes, this value is not the optimal or the final minimum value as the node may receive further lower cost values in future. This forces the node to transmit unnecessarily frequent cost field messages. In order to limit these unnecessary broadcasts in setup phase, the proposed strategy follows a backoff-based cost field establishment algorithm as proposed in [27]. In this algorithm, instead of broadcasting immediately right after receiving a cost value, a node waits for a certain time period proportional to its minimum-cost value. This results in sending minimum cost value only once by a sensor node and there is no need of rebroadcasting.

4.3.2.4 Modes for Updating Status Information

In wireless sensor networks, the cost field status of every sensor node changes rapidly especially if it lies in a currently-used routing path. In order to update the cost field status information and the transmission power levels of wireless sensor nodes with their neighboring nodes, there is a need of running the setup phase very often. However, running the setup phase more frequently exerts an extra overhead. In order to avoid such problem, various modes of operation have been proposed in Chapter 2 out of which only two modes are going to be discussed here.

1. Unicast Acknowledgement Mode (UAM)
2. Broadcast Acknowledgement Mode (BAM)

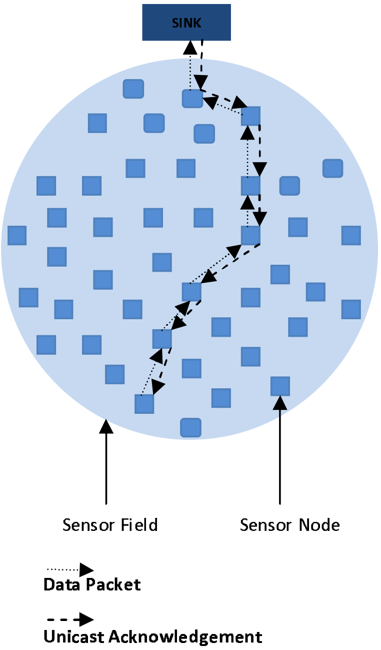


Figure 4.5: Unicast Acknowledgement Mode (UAM)

In Unicast Acknowledgement Mode, each node sends its updated cost field status information as a reply message to the node from which it received the data packet. This updated cost field status information goes with the acknowledgement packet. Upon receiving the acknowledgment packet, transmitting node updates the cost field as well as adjusts the transmission power level with the receiving node. The adjustment of transmission power level is based on the current RSSI value. In this way, all the nodes in a routing path correct their routing tables with the most updated information and update their least-cost neighboring nodes for future packet transmissions. Hence, the setup phase runs only once at the startup. We call it as the Single-Setup (SS) phase with Unicast Acknowledgement Mode.

In contrast, in Broadcast Acknowledgement Mode, every node updates the routing tables of its neighboring nodes by sending a broadcast message containing its updated cost field status information in a reply to every data packet. Fig.s 4.5 and 4.6 represent the Unicast and Broadcast Acknowledgement Modes for updating cost field status information respectively.

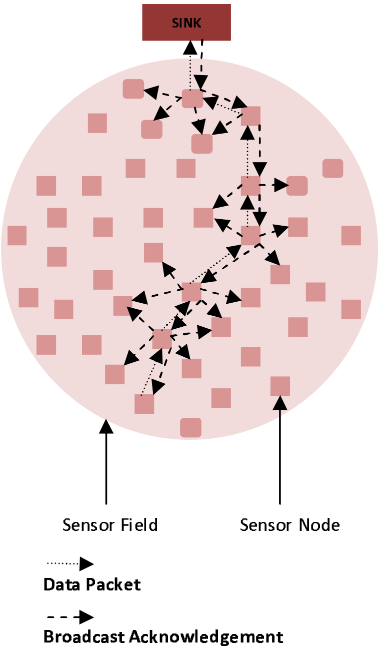


FIGURE 4.6: Broadcast Acknowledgement Mode (BAM)

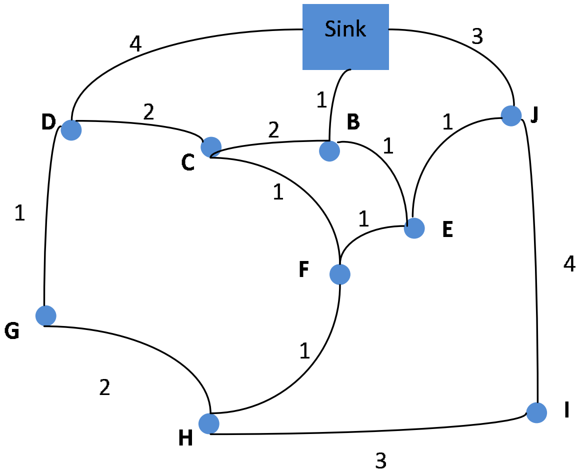


FIGURE 4.7: Example Scenario

In this chapter, UAM is used as a mode for updating status information of sensor nodes.

Table 4.2: Energy Levels of Nodes at some time after the deployment of the Network

ID	Sink	B	C	D	E	F	G	H	I	J
$C_{\mathbf{E}}$	0	2	3	4	5	6	6	8	9	10

4.3.3 An Example Scenario of APCEER

Let us suppose that we have nine sensor nodes along with a sink, deployed as shown in Fig. 4.7. Table 4.2 and Table 4.3 show battery energy values and routing tables of these nodes at some instant of time, respectively.The energy and the link costs are calculated using equations (4.9) and (4.10). First the sink node S broadcasts the advertisement message to nodes B, D and J. This advertisement message contains the cost $\alpha_{\boldsymbol{S}}$=0. Nodes B, D and J receive the message, calculate their respective link costs $\mathrm{C_{L,B\to S}}$, $\mathrm{C_{L,D\to S}}$ and $\mathrm{C_{L,J\to S}}$, then add their link costs to $\alpha_{\boldsymbol{S}}$ to form $\mathrm{C_{B\to S}}$, $\mathrm{C_{D\to S}}$ and $\mathrm{C_{J\to S}}$ respectively. Nodes B, D and J will set PL_{BS}, PL_{DS} and PL_{JS} as the new transmission power levels with S. These values are based upon the current RSSI values. Nodes B, D and J store these information in their routing tables, as shown in Table 4.3. After a certain period of time, which depends on the values of these costs as discussed in section 4.3.2.3, the nodes select the minimum cost $\mathrm{C_{x\to S}}$ from their routing tables, add their own energy cost $\mathrm{C_{E,x}}$ in it forming their respective $\alpha_{\boldsymbol{x}}$ and broadcast it to all of their immediate neighbors including S (In Fig. 4.7, node B broadcasts its advertisement $\alpha_{\boldsymbol{B}}$ to nodes S, C and E; node D broadcasts its advertisement $\alpha_{\boldsymbol{D}}$ to nodes S, C and G; node J broadcasts its advertisement $\alpha_{\boldsymbol{J}}$ to nodes S, E and I). The same procedure also runs at nodes G, C, E and I. All the neighboring nodes of B, D and J take these advertisements as the costs of using these nodes to reach the sink. The sink, S, being one of the neighboring nodes of B, D and J will compare these costs, $\mathrm{C_{S\to B\to S}}$, $\mathrm{C_{S\to D\to S}}$ and $\mathrm{C_{S\to J\to S}}$ with its own cost (i.e. equal to zero) and discard these costs. This will, in other words, mean that S is either the sink itself, or on the path closer to the sink than B, D and J. This process runs on every

Table 4.3: Cost Fields

i	j	$\alpha_{\mathbf{j}}$	$\mathbf{C_{L,i\to j}}$	$\mathbf{C_{i\to j\to Sink}}$	$\mathbf{C_{i\to Sink}}$	$\mathbf{C_{E,\ i}}$	$\alpha_{\mathbf{i}}$	$\mathbf{PL_{ij}}$
B	Sink	0	1	1	1	2	3	-25
	C	8	2	10				-19
	E	9	1	10				-25
D	C	8	2	10	4	4	8	-19
	Sink	0	4	4				-10
	G	15	1	16				-25
J	E	9	1	10	3	10	13	-25
	Sink	0	3	3				-15
	I	26	4	30				-10
C	D	8	2	10	5	3	8	-19
	B	3	2	5				-19
	F	15	1	16				-25
E	J	13	1	14	4	5	9	-25
	B	3	1	4				-25
	F	15	1	16				-25
F	E	9	1	10	9	6	15	-25
	C	8	1	9				-25
	H	22	1	23				-25
G	H	22	2	24	9	6	15	-19
	D	8	1	9				-25
H	I	26	3	29	16	8	22	-15
	G	15	2	17				-19
	F	15	1	16				-25
I	H	22	3	25	17	9	26	-15
	J	13	4	17				-10

sensor node till the last node of the sensor field establishes its routing table. After the setup phase, data communication phase begins. For instance, take node H as a source node. First the node H looks for the potential path-initiating node in its routing table i.e. the node with minimum cost, to reach sink. In our case, it is the node F. Hence, the node H sends the data to the node F. Similar decisions will be made on the other nodes in the potential path until the data reaches the sink.

4.4 Results and Discussion

In this section, performance evaluation of GRACE routing protocol with APCEER is done. The results are first obtained through simulations in Matlab®, and then are validated through an experimental test bed comprising of Sun SPOT® wireless sensor nodes in a realistic dynamic fading environment.

Table 4.4: Parametric Values Used in Simulation

Simulation Parameters	**Values**
Area	1000×1000 m^2
Transmission Range of a Node	200 m
Number of Nodes	200
Tx Power level Range	31 (0 dBm) to 3 (-25 dBm)
Energy Consumption in Rx, E_{Rx}	15.39 mJoules
RSSI Normal Range, γ	0 to -100 dBm
$\gamma_{\mathrm{Th,Lower}}$	-80 dBm
$\gamma_{\mathrm{Th,Upper}}$	-40 dBm
Path-loss Exponent, n	3.0
Data Rate, R_{b}	250 Kbps
Data Packet Length, $Size$	1260 Bytes
Time per Packet, t_{Packet}	0.039 Seconds
Carrier Frequency, f_{c}	2.4 GHz
Initial Energy, E_0	97056 mJoules
Number of Source Nodes	24
Source Node IDs	{144 61 89 93 3 133 145 56 52 142 157 197 95 181 90 161 166 33 79 104 114 92 18 73}
Sink Node ID	57

4.4.1 Simulation and Experimental Setup

The wireless sensor network taken for the simulation setup is comprised of 200 nodes deployed randomly in an area of 1000×1000m^2. Each of these nodes has a communication range of 200 meters and can transmit data and control packets using transmission power levels ranging from 0dBm to -25dBm. Every node has an identical initial energy of 97056 mJoules to match with the hardware battery capacity of a typical Sun SPOT® sensor node. The format for data packet and control packet is maintained as of 1260 bytes and 12 bytes, respectively, in accordance with the communication protocol used in the hardware. As in most of the applications of WSN, sensed data is moved from multiple sources to a single sink; simulations are carried out in the same fashion where 24 nodes act as source nodes. In order to cancel out the effect of limited energy of these source nodes on the performance of the entire network, each of these source nodes is powered externally. This will ensure a true evaluation of the capability of a routing protocol to utilize the batteries of the relay nodes efficiently. Table 4.4 depicts our simulation setup where some more self explanatory parameters are also included in addition to the above mentioned parameters.

Typical values for the energy consumption in transmission and reception of data packets are derived and calculated in Appendix A. The calculations are based on the specific currents drawn by different components of a Sun SPOT® node listed in Table 4.5. The current drawn shown in Table 4.5 by the radio in Tx mode is 17.4mA when the Tx power is at its maximum i.e. at 0dBm. In case of APCEER where transmission power level is adjusted in the range from the maximum to the minimum, current drawn values are used according to Table 4.6 where corresponding values for the energy consumption in mJoules is also listed. The current draw values in Table 4.5 and Table 4.6 are taken from the data sheets of Sun SPOT [66] and CC2420 [16] respectively and are utilized in simulation for their onward harmony with the hardware results. In Table 4.5, deep sleep mode means the processor and sensor board are both powered down; while shallow sleep means devices are active; however, there are no active threads.

In order to receive data packets successfully, RSSI must be within the acceptable range. For the given simulation, the minimum acceptable RSSI value is set to -80 dBm, while the maximum RSSI to -40dBm.

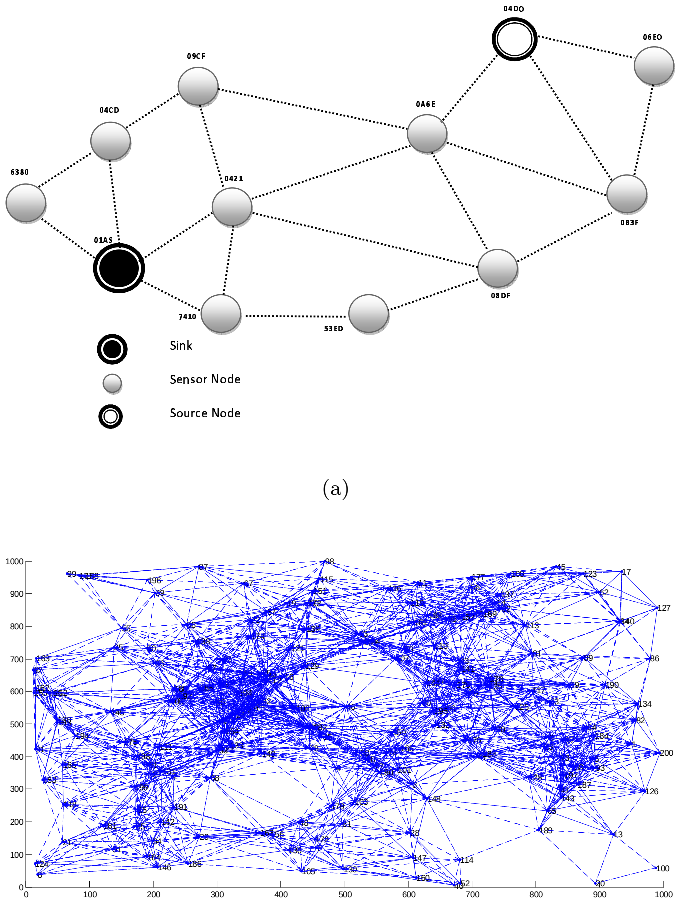
Although simulation tools other than Matlab® (such as NS2/NS3 or Omnet++, namely, the de-facto solutions for performance evaluation in wireless sensor networks) are usually preferred by the research community; however, due to the

Table 4.5: Current Draw Values Used by Sensor Nodes

Processor Board State	**Current Drawn by Processor or Intrinsic Electronics or both**	**Current Drawn by Sensor Board with Single Sensor**	**Current Drawn by Radio at 0dBm Tx Power Level**		**Total Current Drawn by Single Sensor**	
			Transmission Mode	Reception Mode	Transmission Mode i_{Tx}^{31}	Reception Mode i_{Rx}
Deep Sleep Mode	33 μA	0	0	0	33 μA	33 μA
Shallow Sleep	24 mA	0	0	0	24 mA	24 mA
	24 mA	0	17.4 mA	19.7 mA	41.4 mA	43.7 mA
	24 mA	7 mA	0	0	31 mA	31 mA
	24 mA	7 mA	17.4 mA	19.7 mA	48.4 mA	50.7 mA
Awake, Actively Calculating	80 mA	0	0	0	80 mA	80 mA
	80 mA	0	17.4 mA	19.7 mA	97.4 mA	99.7 mA
	80 mA	7 mA	0	0	87 mA	87 mA
	80 mA	7 mA	17.4 mA	19.7 mA	104.4 mA	106.7 mA

Table 4.6: Current Draw and Energy Consumption Values of Available Power Levels Used

Transmit Power Level, k	**RF Output Power (dBm)**	**Current Drawn $i^k_{\mathbf{Tx}}$ (mA)**	**Energy Consumption $E^k_{\mathbf{Tx}}$ (mJ)**
31	0	17.4	14.86290
27	-1	16.5	14.73303
23	-3	15.2	14.54544
19	-5	13.9	14.35785
15	-7	12.5	14.15583
11	-10	11.2	13.96824
7	-15	9.9	13.78065
3	-25	8.5	13.57863



(a)

(b)

Figure 4.8: Sensor Mote Deployment (a) Experimental (b) Simulation

involvement of more physical layer components in the proposed routing strategy, we preferred Matlab® over rest of the simulators for its mathematical and analytical strength and flexibility in modeling various network scenarios with varying fading conditions. Moreover, testing the proposed routing strategy on a realistic test-bed adds more value to our performance comparative analysis.

In order to evaluate the proposed protocol in a realistic practical environment, a test-bed of Sun SPOT® [66] (Small Programmable Object Technology) sensor motes is used. 12 Sun SPOT sensor motes are deployed in a laboratory. The sensor motes deployment is shown in Fig. 4.4.1 along with deployment for simulation. The specifications of these sensor motes taken from [66] are listed in Table 4.7. The reason for choosing Sun SPOT® units is that these nodes possess 400MHz high speed processor with 1MB RAM which is suitable for protocols with high processing overhead. The nodes are tiny (41 x 23 x 70 mm), light weight (54 gms) and, therefore, are fit for most of the application areas where size and weight do matter.

TABLE 4.7: Sun SPOT® Specification

Hardware Parameters	**Values**
RAM memory	1MB
Flash memory	8MB
Dimensions	41 x 23 x 70 mm
Weight	54 gms
Processor Speed	400 MHz
Radio	CC2420
Frequency	2.4 GHz
IEEE Standard	802.15.4
Battery	3.7V rechargeable lithium-ion battery
Sensors	Light, temperature and accelrometer

4.4.2 Simulation and Experimental Results

As sensor nodes are energy constrained nodes, therefore, energy saving is a challenging task. The main aim of the proposed protocol, APCEER, is to reduce the

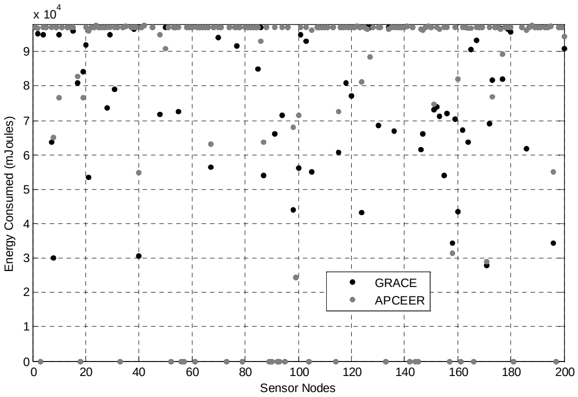


Figure 4.9: Simulation Results of Energy Consumption by Sensor Nodes using GRACE and APCEER

communication interference among sensor nodes, establish energy-efficient routes from source to sink and thus, to save energy of each and every sensor node in the network. This results in an overall increase of network lifetime. Energy depletion values of deployed sensor nodes till the end of the network in simulations and experiment are shown in Fig. 4.9 and Fig. 4.10, respectively. The lifetime of the network is the time till the network is partitioned or unable to be utilized. This is done in the simulation by considering the fact that either neighbors of the sink or neighbors of all the selected source nodes are died. Fig. 4.11 shows a comparison between the lifetime curves of GRACE and the proposed APCEER obtained through simulation and experimental campaign. The lifetime curves obtained in experiment are scaled up from 12 nodes to 200 nodes to compare them with simulated results. Simulation and experimental results show a similar trend. From the Fig. 4.9, Fig. 4.10 and Fig. 4.11, it can be seen that APCEER's energy consumption trend is almost similar to that of GRACE; however, the network lifetime of the APCEER is far better than the GRACE, clearly visible from simulations as well as from experimental results. Improvement in the lifetime of the network by using APCEER is basically the outcome of efficient utilization of transmit power. The saving in power in turn prolonged the network lifetime.

Transmission power control (TPC) strategies tune the transmission power ac-

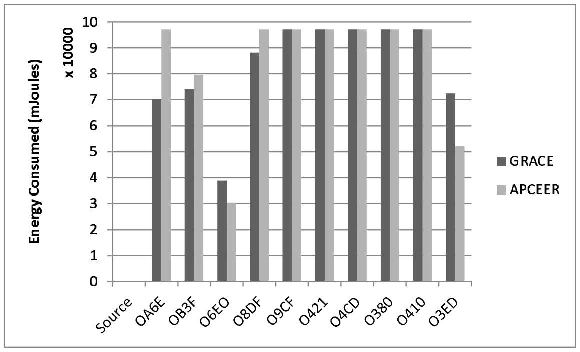


FIGURE 4.10: Experimental Results of Energy Consumption of Sensor Nodes using GRACE and APCEER

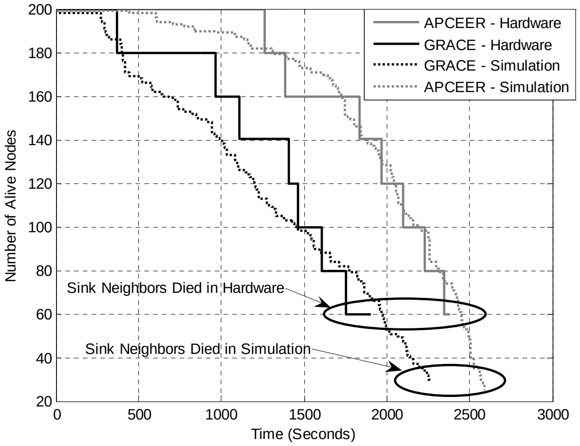


FIGURE 4.11: Lifetime Comparison of Sensor Nodes using GRACE and APCEER

cording to current propagation environment for successful transmission of data packets. In the proposed routing scheme, APCEER, the maximum transmission power level is only used if the RSSI crosses the minimum acceptable level; otherwise, the lower transmission power levels are used instead. The proposed protocol, APCEER, tries to use minimum transmission power level provided the RSSI is within its threshold region. Fig. 4.12 shows the power level switching of a node for the first 50 seconds. It is clear from the figure that most of the time, TPC module at a node tries to keep the power level at its minimum i.e. -25 dBm. Only at the startup, it uses high transmission power level. This is due to the reason

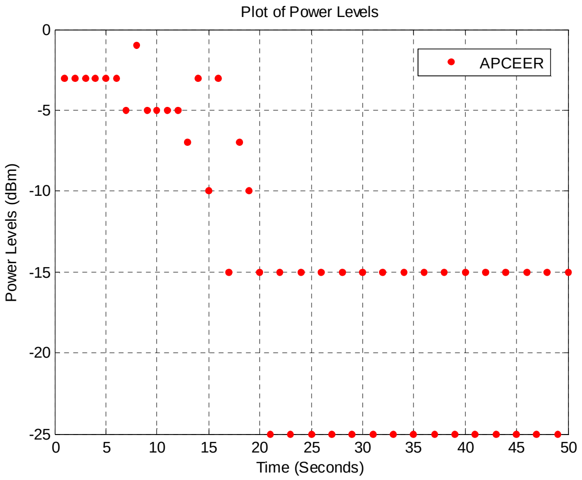


FIGURE 4.12: Power Levels Switching of a Sensor Node for the first 50 seconds using APCEER

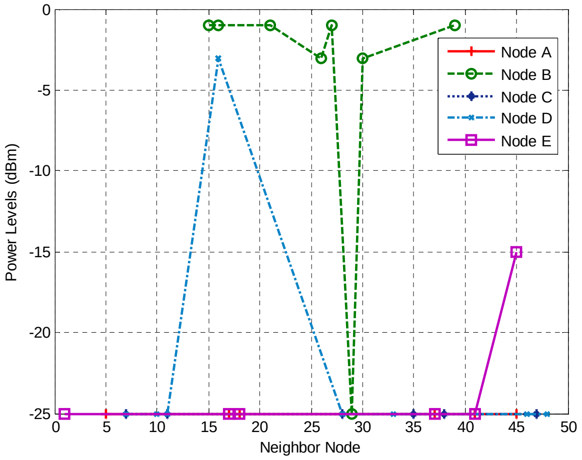


FIGURE 4.13: Power Level Switching of 5 different Sensor Nodes Using APCEER

that at the beginning node communicates with neighbors ensuring good quality wireless links. Therefore, for successful transmission of data packets, a node uses high transmission power level at the beginning. Afterwards, the node uses either -15 or -25dBm power level for communication with rest of the time. Fig. 4.13 shows the power levels of five different sensor nodes with their neighbors. Only node B switches its power level most of the time; all the other nodes try to adjust their power level at the minimum level i.e. -25 dBm. Fig. 4.14 shows the number

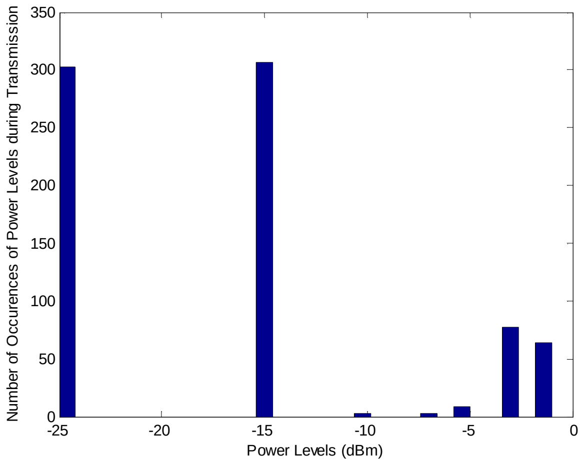


Figure 4.14: Occurrences or Frequency of Power Levels at a Single Node using APCEER

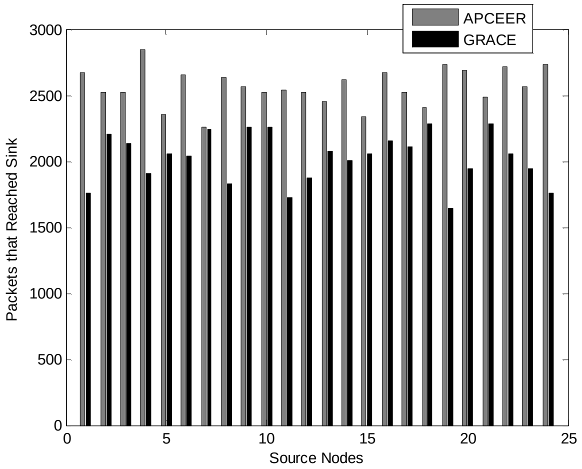


Figure 4.15: Packet Transmissions by Source Nodes using GRACE and APCEER

of occurrences of power levels adjusted by a single sensor node during its lifetime. Most of the time, the power level is adjusted at -15 dBm and -25 dBm, which are the minimum power levels.

Transmission of data packets is an important and major phenomenon of any communication network. One of the desired goal of this work is to increase the transmission capability of each sensor node in the network. Fig. 4.15 shows packet transmissions originated from 24 source nodes which are selected as source node.

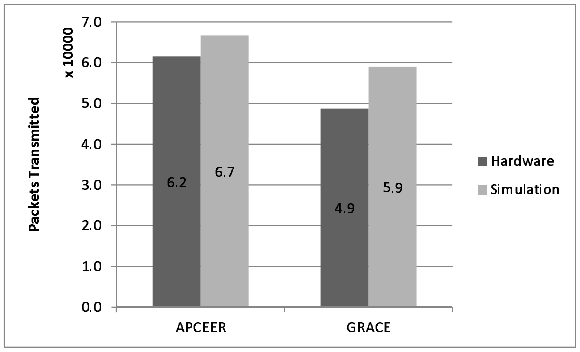


FIGURE 4.16: Packet Transmission Comparison of Sensor Nodes using GRACE and APCEER

The energy of all the source nodes and the sink node is set to infinite. It can be observed that all the source nodes are transmitting almost similar number of data packets and are sending them to sink using a particular routing strategy i.e., GRACE or APCEER. Packet transmissions by source nodes occur in a round robin fashion which results in uniform utilization of the selected source nodes. In addition, the number of data packets transmitted by the source nodes are fewer than the number of data packets transmitted by other sensor nodes. The reason is that the source nodes do not act as relay nodes i.e. these nodes do not appear on any of the selected routing paths. Fig. 4.16 shows a comparison of packet transmissions including number of retransmissions using GRACE and APCEER obtained in experiment and simulation. Fig. 4.17 shows the experimental and simulation results of overall network energy consumed. The difference of the energies consumed in GRACE and APCEER using simulations is only 1.07%, while the same difference using hardware experiment is 1.4%. As the difference is too minor, therefore one can ask where the savings of the proposed APCEER methodology are? The savings in energy are used in the transmission of more data packets, by prolonging the network lifetime. These savings are also evident from Fig. 4.11 and Fig. 4.16. It can thus be concluded from the above discussion that APCEER is more energy efficient than GRACE.

Fig. 4.18 shows the energy efficiency plots of the GRACE and APCEER protocols.

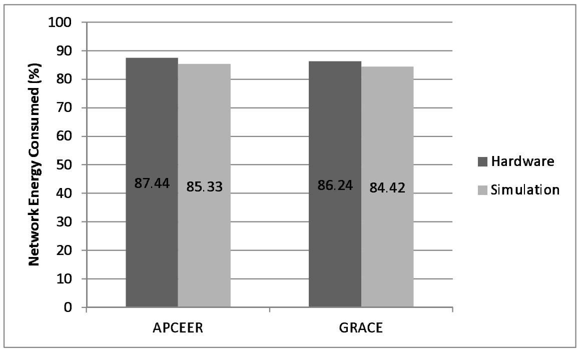


FIGURE 4.17: Network Energy Consumed using GRACE and APCEER

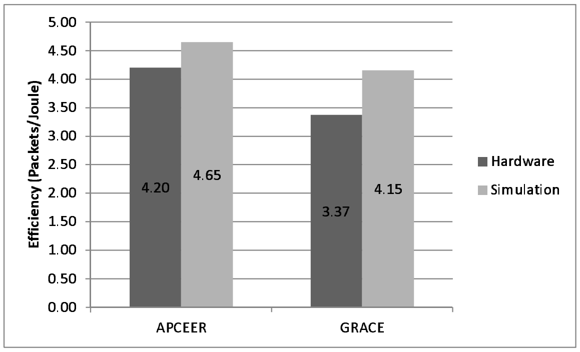


FIGURE 4.18: Efficiency of GRACE and APCEER

Energy efficiency of an energy-aware routing strategy can be defined in terms of number of packet transmitted per Joule consumed as

$$\eta_{\text{Energy}} = \frac{n}{e} \qquad \textit{Eq (4.12)}$$

where, η_{Energy} is the energy efficiency, n is the total number of packets transmitted and e is the overall network energy consumed in Joules. From the figure, it is clear that APCEER again shows better energy efficiency in terms of each joule utilization. This result confirms the discussion made for Fig. 4.17.

4.5 Conclusion

Tuning the transmit power of an energy constrained node at runtime in dynamic fading environment has been a challenging task since the start of last decade. Wireless sensor networks having scarce resources need energy-aware transmission strategies that are adaptive to time-varying fading conditions. In general, effective power control results in an improved connectivity, optimized coverage, less battery utilization, increased node-lifetime and maximized throughput. In this article, we have proposed a novel energy-aware routing strategy that focuses on the problem of dynamic route discovery embedded with effective power control mechanism for energy constrained wireless sensor nodes deployed in an urban environment communicating over time-varying fading channels. The proposed adaptive power control for energy efficient routing (APCEER) strategy is based on dynamic cost field establishment with a power control mechanism that chooses a suitable transmit power level according to propagation conditions. It has been shown that the proposed scheme outperforms the existing energy-aware routing strategies that are not equipped with a power control mechanism. The proposed APCEER can thus be utilized in urban applications of wireless sensor networks that need ultra efficient utilization of energy by power-constrained nodes operating in severe fading conditions.

Chapter 5

CONCLUSIONS AND FUTURE WORK

5.1 Summary

The dissertation begins with the introductory chapter where the main goals of the work have been outlined. In this chapter, the area of wireless sensor networks has been explained along with current research issues and challenges. The importance of the term *energy-aware routing* in the field of low cost, low data rate and low battery power sensor nodes in a WSN has been discussed in detail. Problem statement and the proposed methodology have also been presented in the chapter.

Chapter 2 discussed the contribution about GRAdient Cost-field Establishment (GRACE) routing protocol, that focuses on two cost factors: energy of nodes and link quality. A detailed discussion about the significant previously published works on energy-aware routing are mentioned. The proposed GRACE protocol has been presented with detailed description of the approach along with discussions on different modes of operation.

Chapter 3 deals with a discussion of transmission power control strategies. In order to improve the performance of GRACE in terms of energy of nodes and lifetime of the network, a transmission power control (TPC) strategy, MODTPC, has been proposed. The benefits of the proposed TPC strategy in terms of energy saving has been discussed in detail. Simulation results along with experimental results are also presented at the end of chapter 3.

Chapter 4 introduces another methodology, Adaptive Power Control based Energy Efficient Routing (APCEER), for energy efficient routing in WSNs based on transmission power control strategy. As discussed in previous chapters, energy consumption is a very important aspect of the WSNs due to the fact that sensor nodes have limited battery power and are mostly unattended. In the proposed protocol, APCEER, the idea of transmission power control has been applied on the basic energy-aware routing approach of GRACE. Proposed methodology of APCEER, computer simulations and experimental results on real test-bed represent a significant contribution into the area of minimizing the energy consumption in resource-constrained WSNs.

5.2 Conclusions

In this dissertation, the problem of energy-aware routing in wireless sensor networks has been addressed. Mainly, two energy-aware routing strategies, GRAdient Cost-field Establishment (GRACE) Routing and Adaptive Power Control based Energy Efficient Routing (APCEER), have been proposed.

In GRAdient Cost-field Establishment (GRACE) routing, a gradient of cost fields has been exploited to explore the energy-efficient routes for the delivery of data from any source node to the sink. GRACE, based on energy and link quality cost factors, has been designed to work on the selection of routing paths that contain both high-power nodes and good-quality wireless links. Through theoretical analyses, computer simulations and test-bed measurements, it has been shown that the proposed dynamic routing, GRACE, helps achieve the desired system performance under dynamically changing network conditions. It has been observed that GRACE, on one hand, reduces both energy consumption and communication-bandwidth requirements and on the other hand, prolongs the network lifetime. The proposed algorithm, GRACE, has been compared with one of the best existing energy efficient routing algorithms, GRAB.

Although GRACE is an energy-aware routing protocol designed specially for resource constrained wireless sensor nodes, however, limited battery resource at a sensor node coupled with the hostile multi-path fading propagation environment makes the task of the network to provide reliable data services with an enhanced lifetime, challenging. Tuning the transmit power of an energy constrained node at runtime in dynamic fading environment has always been remained a challenging task. Wireless sensor networks having scarce resources need energy-aware transmission strategies that are adaptive to time-varying fading conditions. In general, effective power control results in an improved connectivity, optimized coverage, less battery utilization, increased node-lifetime and maximized throughput.

A novel energy-aware routing strategy, APCEER, has also been proposed. APCEER focuses on the problem of dynamic route discovery embedded with effective power control mechanism for energy constrained wireless sensor nodes deployed in an urban environment communicating over time-varying fading channels. The proposed APCEER strategy is based on dynamic cost field establishment with a power control mechanism that chooses a suitable transmit power level according to propagation conditions. It has been shown that the proposed scheme outperforms the existing energy-aware routing strategies that are not equipped with a power control mechanism. The proposed APCEER can thus be utilized in urban applications of wireless sensor networks that need ultra-efficient utilization of energy by power-constrained nodes operating in severe fading conditions.

5.3 Prospective Future Work

The research work in this dissertation can be extended for its onward use in many useful future applications.

The proposed energy-aware routing strategy, APCEER, can be upgraded to be used in a cluster-based networking approach like Quasi Centralized Clustering Approach (QCCA) [87]. In QCCA, the local base station (cluster-head) is assumed to be a high-energy node. However, if the base station is a energy-constrained node, it would die quickly as it is being heavily utilized. Using APCEER along with QCCA, one can take benefit of both clustering and transmission power control in routing data in WSNs.

The proposed energy-aware routing strategy, APCEER, can also be upgraded to be used in real-time applications by taking data deadlines into account.

APPENDICES

Appendix-A

Appendix A explains the procedure for calculating current drawn and energy consumed by the LEDs.

A1 - Energy Consumption by LEDs

LEDs (if equipped) on a sensor node also use power from the pool of battery. Sun SPOT is the sensor node used by the authors to evaluate the proposed protocol for its onward comparison with existing energy-aware routing strategies. The currents drawn by a single LED mounted on a Sun SPOT shown in the Table 5.1 are based on the information provided in [66].

TABLE 5.1: Current Drawn by Sun SPOT LEDs

LED	**Brightness**	**Current Drawn**
All elements	full	25 milliampere
All elements	half	12.5 milliampere
Blue element	full	10 milliampere
Blue element	half	5 milliampere
Red element	full	9 milliampere
Red element	half	4.5 milliampere
Green element	full	5 milliampere
Green element	half	2.5 milliampere

The LEDs used in the experiments are in half-brightness mode. There are two types of LEDs used on a Sun SPOT node, i.e. *Power LED* and *Activity LED.* Power LED has a continuously-glowing green element; while activity LED glows only when a node transmits or receives. In transmission mode, this LED glows in green; while turns red when the radio is in reception mode.

A1.1 Energy Consumption by LEDs When Node is in Receiving Mode

Energy consumption in Joules by LEDs in reception mode can be calculated using the following current equations

$$i_{\mathrm{LED}}^{\mathrm{Rx}} = i_{\mathrm{Green}}^{\mathrm{Pow}} + i_{\mathrm{Red}}^{\mathrm{Act}} \qquad \textit{Eq (5.1)}$$

where, $i_{\mathrm{LED}}^{\mathrm{Rx}}$ is the current drawn by the LED when a node is in receiving mode, $i_{\mathrm{Green}}^{\mathrm{Pow}}$ is the current drawn by the power LED having only green element with half-brightness and $i_{\mathrm{Red}}^{\mathrm{Act}}$ is the current drawn by the activity LED having only red element with half-brightness.

Multiplying $i_{\mathrm{LED}}^{\mathrm{Rx}}$ by t_{Packet} (from Table 4.4) and v, the voltage level at which the node is operating, we get energy consumed by LEDs when a node is in receiving mode, $\mathrm{E}_{\mathrm{LED}}^{\mathrm{Rx}}$, as follows

$$\mathrm{E}_{\mathrm{LED}}^{\mathrm{Rx}} = i_{\mathrm{LED}}^{\mathrm{Rx}}\ v\ t_{\mathrm{Packet}} \qquad \textit{Eq (5.2)}$$

A1.2 Energy Consumption by LEDs When Node is in Transmission Mode

Energy consumption in Joules by LEDs in transmission mode can be calculated using the following current equations

$$i_{\mathrm{LED}}^{\mathrm{Tx}} = i_{\mathrm{Green}}^{\mathrm{Pow}} + i_{\mathrm{Green}}^{\mathrm{Act}} \qquad \textit{Eq (5.3)}$$

where,$i_{\mathrm{LED}}^{\mathrm{Tx}}$ is the current drawn by the LED when a node is in transmitting mode, $i_{\mathrm{Green}}^{\mathrm{Pow}}$ is the current drawn by the power LED having only green element with half-brightness and $i_{\mathrm{Green}}^{\mathrm{Act}}$ is the current drawn by the activity LED having only red element with half-brightness.

Multiplying $i_{\text{LED}}^{\text{Tx}}$ by t_{Packet} (from Table 4.4) and v, we get energy consumed by LEDs when a node is in transmitting mode, $\text{E}_{\text{LED}}^{\text{Tx}}$, as follows

$$\text{E}_{\text{LED}}^{\text{Tx}} = i_{LED}^{Tx}\ v\, t_{\text{Packet}} \qquad \textit{Eq (5.4)}$$

Appendix-B

Appendix B explains the procedure for calculating current drawn and energy consumed by the radio in reception mode.

B1 - Energy Consumption by Receiver

When a node receives a packet, it uses both power and activity LEDs. The processor board state is awake, actively calculating and the radio is in receiving mode. The net energy consumed by the node is calculated as follows

$$\text{E}_{\text{Rx}} = i_{\text{Rx}}\ v\, t_{\text{Packet}} + \text{E}_{\text{LED}}^{\text{Rx}} \qquad \textit{Eq (5.5)}$$

where, E_{Rx} is the total energy consumed, i_{Rx} (from Table 4.5) is the total current drawn by a node in receiving mode with a processor having state awake and actively calculating and $E_{\text{LED}}^{\text{Rx}}$ (from Appendix A1.1) is the energy consumed by LEDs when the node is in receiving mode.

Appendix-C

Appendix C explains the procedure for calculating current drawn and energy consumed by the radio in transmission mode.

C1 - Energy Consumption by Transmitter

When a node transmits a packet, it also uses both power and activity LEDs. The processor board state is awake, actively calculating and the radio is in transmitting mode using k^{th} transmission power level. The net energy consumed in Joules by the node can be rewritten from equation (4.4) in terms of current and voltage values as

$$\mathrm{E}_{Tx} = i^{k}_{\mathrm{Tx}}\ v\ t_{\mathrm{Packet}} + \mathrm{E}^{\mathrm{Tx}}_{\mathrm{LED}} \qquad \textit{Eq (5.6)}$$

where, E_{Tx} is the total energy consumed and i^{k}_{Tx} is the total current drawn by a node in transmitting mode with transmission power level k. i^{k}_{Tx} depends on the extent of power consumed by local oscillator and power amplifiers, used in transmitter. The possible values of i^{k}_{Tx} are listed in Table 4.6 and depend upon the transmission power level used. $\mathrm{E}^{\mathrm{Tx}}_{\mathrm{LED}}$ is discussed in Appendix A 1.2.

Appendix-D

Appendix D explains the procedure for calculating current drawn and energy consumed by the radio in listening mode.

D1 - Energy Consumption by Listener

When a node neither transmits nor receives, it is in listening mode where the node is in shallow sleep and only the power LED is ON. The total energy consumed in listening mode is given by the following equation.

$$\mathrm{E}_{\mathrm{Lx}} = (i_{\mathrm{Lx}} + i^{\mathrm{Pow}}_{\mathrm{Green}})\ v\ t_{\mathrm{Packet}} \qquad \textit{Eq (5.7)}$$

where, E_{Lx} is the energy consumed in listening, i_{Lx} is the current drawn by a node in shallow sleep mode with radio on. $i^{\mathrm{Pow}}_{\mathrm{Green}}$ is discussed in Appendix A 1.1.

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