國立中山大學 電機工程學系

博士論文

Lifetime Maximization Schemes with Optimal Power Control for Multimedia Traffic in Wireless Sensor Networks

在無線感測網路中針對多媒體資料流具有最佳功率控制的生存時間最大化的解決方法

研究生：盧怡仁 撰

指導教授：許蒼嶺 博士

中華民國 九十八 年 五月

摘 要

在無線感測網路中，有效改善耗電以及延長節點使用壽命是很熱門的研究主題。本論文中，為了維持資料串流品質穩定的情況下，我們提出如何調整最佳的傳輸功率以便找出解決路徑生存時間最大化的方法。為了解決此最大化的問題，我們將解決方案分為兩部份進行分析。第一部份，我們首先考量如何降低耗電的問題。在無線節點傳送多媒體資料時，如果為了減少節點耗電量而降低傳送功率，這可能會影響多媒體的品質。為了兼顧節點的耗電量以及維持穩定的多媒體傳輸品質，我們提出一個有效率的路徑搜尋方案。發送端提出一個品質維持率，這個方案必須根據節點通道情況調整其最佳的傳送功率，以達到穩定的多媒體傳輸品質，最終再從有效路徑中找尋最低耗電量的路徑。

在本論文的第二部份，延續第一部分對多媒體品質的定義，我們進一步考慮在無線感測網路中如何延長節點壽命，同時想要延長節點使用時間而且維持多媒體品質的穩定度是屬於非線性最佳化的範疇，其可轉化成一個最大-最小化組合型的數學方程式。為了解決這個方程式，我們提出兩個方法：route-associated power management (RAPM) 與 link-associated power management (LAPM)。對於運算資源有限的節點，RAPM 方法可藉由簡化運算條件降低運算量所耗費的資源，並且能夠快速地計算出每條路徑的使用壽命，找出最長壽的路徑。除此之外，若運算資源足夠的情況下，可以採用 LAPM 方

法計算出更為準確的結果，同時針對路徑上的各個節點配置最適合的傳送功率。最後，我們分析這兩種解決方案，發現使用 LAPM 方法其結果相當近似於暴力法求解的結果。

Abstract

Power saving for extending session lifetime is an important research subject in wireless sensor networks (WSNs). Recognizing the fact that Quality of Service can be deteriorated by insufficient transmit power, this work studies how to minimize power consumption while achieve a satisfactory QoS of data streams in WSNs. A cross-layer routing scheme is proposed to maximize session lifetime by adjusting individual transmit power on intermediate nodes. The thesis is divided into two major parts for analyzing our proposition. In the first part, we propose an efficient routing scheme with optimal power management and on-demand quality control for WSNs. When source node issues a QoS provision for route discovery, an adjustment of transmitting power is computed for each pass-by node by taking into its individual wireless link account. Then, an optimal route associated with lowest power consumption and consistent QoS can be selected among all of the candidate routes. In the second part, by following the definition of QoS criterion in the first part, we further consider the problem of how to balance the needs on constraining end-to-end quality and prolonging lifetime in an established route. The problem can be interpreted as a non-linear optimization paradigm, which is then shown to be a max-min composite formulation. To solve the problem, we propose two methods, (1) route-associated power management (RAPM), and (2) link-associated power management (LAPM). Considering computation-restricted sensor nodes, the RAPM scheme is two-fold simplification; not only it can reduce power computation, but it also quickly determines the longest lifetime and proper transmit power for nodes. On the other hand, if computational cost is not a major concern in a sink node, the LAPM algorithm is more suitable than RAPM to solve the lifetime maximization problem, in terms of accuracy. Finally, we analyze the performance of these two methods. The results demonstrate that the LAPM scheme is very comparable to a heuristic approach.

Tables of Contents

摘 要 i
Abstract iii
List of Figures vii
List of Tables viii
Chapter 1 Introduction 1
1.1 Motivation 1
1.2 Proposed Schemes on WSN 4
1.2.1 Efficient Power Control on WSN 4
1.2.2 Lifetime Maximization on WMSN 7
1.3 Organization of the Dissertation 9
Chapter 2 Survey of Literature 11
2.1 Works on Power Management 11
2.1.1 Efficient Power on QoS Criterion 12
2.1.2 Power Management on Link Scheduling 13
2.1.3 Power-aware Protocol 14
2.2 Works on Lifetime Maximization 15
2.2.1 Topics on Network Lifetime 15
2.2.2 Topics on Multicasting 17
2.2.3 Topics on Efficient Routing 18
2.2.4 Topics on Special Purposes 19
Chapter 3 Minimization of Power Consumptions 22
3.1 Model Description 22
3.2 Definition of QoS Criterion 25
3.3 Route Selection with Power Minimization 30
3.4 Optimal Power Determination 34
3.5 Power Control for Multimedia 39
Chapter 4 Lifetime Maximization 41

4.1 How to Maximize Lifetime 41
4.1.1 System Description 41
4.1.2 Problem Formulation 43
4.2 Route-Associated Power Management 46
4.3 Link-Associated Power Management 53
Chapter 5 Numerical Analysis 62
5.1 Analysis of Power Control 62
5.1.1 Comparison with a Previous Work 62
5.1.2 Study of Different Parameters 64
5.1.3 Numerical Results 66
5.2 Case in Heterogeneous Networks 68
5.3 Analysis of Session Lifetime 75
Chapter 6 Conclusions and Future Works 84
6.1 Conclusions 84
6.2 Future Works 85
Bibliography 87
Vita 94

List of Figures

Figure 3-1: Multimedia streaming in a wireless multi-hop network. 24

Figure 3-2: P_{fe} and GP_{fe} comparison for DSPK 30

Figure 3-3: Pseudo-Codes for a Wireless Sensor Node. 34

Figure 5-1: Comparisons in total power consumption. 63

Figure 5-2: Optimal power vs. *NG* ratio. 65

Figure 5-3: Average power consumption vs. retransmission times. 66

Figure 5-4: Topology used in retrieving an optimal route. 66

Figure 5-5: Minimum power cost for each path. 68

Figure 5-6: Video streaming in a heterogeneous network. 69

Figure 5-7: Average power consumption without using ARQ scheme. 71

Figure 5-8: End-to-end frame error rate on each route (without ARQ). 72

Figure 5-9: Average power consumption by using ARQ scheme. 73

Figure 5-10: End-to-end frame error rate on each route (with ARQ). 73

Figure 5-11: Comparison of power saving between Methods 1 and 2. 74

Figure 5-12: Network topology used for lifetime simulation. 75

Figure 5-13: Calculation of route lifetime by adopting the RAPM approach. 78

Figure 5-14: The variation of judgment factor over route lifetime. 78

Figure 5-15: Discrepancy percentage between the RLM algorithm and heuristic determination. 80

Figure 5-16: Iterations needed for lifetime convergence in the RLM algorithm. 80

Figure 5-17: Lifetime on route 1 determined by the RLM algorithm. 82

Figure 5-18: Route lifetime with respect to hop count. 83

List of Tables

Table 5-1: Given Parameters for Power Minimization 64

Table 5-2: Optimal Transmit Power at $N = 3$ 67

Table 5-3: System-related parameters for lifetime maximization. 76

Chapter 1 Introduction

1.1 Motivation

With the advent of wireless communications, various applications in traditional wired networks have been migrated into portable devices, even into wireless sensors (e.g., camera or mini-microphone). Due to the limited energy available in these devices, power saving in wireless networks [1] becomes a critical issue concerning how to prolong the working time of the devices, especially in the aspect of wireless sensor network (WSN). Specifically, WSN may be a single-hop or multi-hop system, may be Ad-hoc network, and may be power-limited. However, wireless Ad-hoc networks may not be power-limited for nodes. Therefore, in this thesis, our research topic is contributed to the balance of both power control and lifetime maximization with quality constraint in WSN environments. In general, the capability of traditional sensors is limited to simply collecting some information with low bit rates, while current advanced sensors feature multimedia communication. Therefore, as far as wireless multimedia sensor networks (WMSN) [2] are concerned, advanced power management is crucial for network planner in deploying a consistent network system.

In WSNs, it is important for a multimedia session to constrain a satisfactory quality-of-service (QoS) and prolong the session lifetime on an established route. To this end, we attempt to adjust transmit power of intermediate nodes to maximize session lifetime. Unfortunately, increasing session lifetime usually involves reducing power consumption, which may deteriorate QoS. Hence, to balance power efficiency and multimedia quality in WSN or WMSN, we need to tackle the following problems.

- How to minimize power consumption of wireless nodes under a QoS constraint.
- How to determine a best route associated with minimum power consumption.
- How to maximize the lifetime of multimedia sessions and how to adjust power usage of wireless node.

The minimization of power consumption is a primary issue in WSNs. Besides studying this issue, a majority of our efforts are put on investigating how to maximize the session lifetime for individual route or network-wide.

Up to now, it remains an unsolved problem in a wireless network concerning the optimization of both transmit power and QoS constraints, such as packet loss rate, latency, jitter tolerance, and throughput. Although the reactive (on-demand) routing protocols, which retrieve a suitable path according to criteria of minimizing link cost and balancing traffic load, have been developed to handle the wired networks for the past decade, those protocols may not be applicable to wireless networks in terms of better power management. This is because there are more factors, such as power consumption, noise interference, and node mobility, needing to be considered in wireless communications. Thus, the routing problem in a heterogeneous network where wired and wireless links are interoperated together is worthy of further investigating, especially on the relationship between power consumption and QoS retaining.

To achieve a consistent throughput QoS, we need to sustain a low bit-error rate in a route passing multiple wired and wireless links. This may be done by increasing the transmit power of wireless node, so that the noise or interface can be suppressed, and hence the fluctuating bit-error rate could be gradually reduced to our desired level. In other words, *signal-to-noise ratio* (SNR) must be consistently maintained above a certain threshold. However, increasing transmit power sacrifices the battery life. To balance the power consumption and link quality, this dissertation presents a power control scheme to maintain an acceptable end-to-end (*e2e*) quality in a heterogeneous network.

Apart from managing power control for wireless nodes, quality of multimedia session is also very sensitive to the frequencies of re-connection or re-routing. Considering multimedia streams flooding in WMSN, so encouraged to us to research a power-efficiency problem is how a QoS-guaranteed session may be set up on a durable route without being disturbed by out of battery. However, in reality, the mentioned-above case is a challenging task since re-routing process may result in worse quality when a relay node on the route runs out of energy. By contrary, in the case of a long streaming video passing through a stable and consistent route, the acceptable quality of the video can be displayed to its receiving side. In the worst case, once some relay nodes on the route run out of battery, a backup route should be immediately established as video is playing. This will cause occasional session discontinuity and, furthermore, visual fluency and quality deterioration. To this end, our works in this dissertation are dedicated to making the service time of delivering multimedia sessions on each individual route as long as possible.

1.2 Proposed Schemes on WSN

1.2.1 Efficient Power Control on WSN

Unlike wired networks, an interference problem on a WSN is a significant effect if we require a fixed and stable throughput for all wireless links. First of all, how to sustain a fixed bit-error rate on wireless links is essential. Bit-error rate in wireless communications could be gradually reduced, if the transmit power of wireless node is gradually increased to suppress noise or interference. For the past decades, many works have developed for on-demand routing protocols to the wired networks. The routing protocols adopting in current wired networks are able to retrieve one suitable path according to the criterion of minimizing link cost and balancing traffic load. However, they are not suitable for wireless networks since the factors of wireless communications have to be considered. In a wireless sensor network, it is of importance not only to satisfy an end-to-end QoS requirement, but also to manage the power consumption of a wireless node. Therefore, in this dissertation, we present a power minimization scheme with an end-to-end quality constraint.

An example scenario is illustrated as follows. When video slices captured by a CCD camera are streaming over a heterogeneous network to a destination, we anticipate the streaming must satisfy a certain quality in terms of dots per inch (DPI) or frames per second (FPS) for a period of time. Hence, it is necessary to jointly optimize the power consumption cost and end-to-end QoS requirement. To provide user-level visible quality in a video streaming environment, we represent an end-to-end QoS criterion as frame-error probability rather than bit-error rate. Finally, for robustness in cross-layer design, we consider link-layer flow control algorithms, namely the forward error correction (FEC) and the automatic repeat request (ARQ), in the power optimization problem. In particular, we will formulate a frame-error probability based on ARQ mechanism and specify an end-to-end cost with on-demand quality.

Before establishing one long-lived path with an on-demand quality in WSNs, a source node must predefine an end-to-end frame error rate according to what quality it requires. Mathematically, we can formulate a power-cost equation at any error rate and then minimize the power cost in compliance with a given rate. Furthermore, the problem on power optimization is shown in this thesis to have a closed form solution, which is comparable to the heuristic result, i.e., an exhaustive search to the optimal solution. The proposed approach not only allows the optimal path to be discovered very quickly, but also enable the power consumption on the participant nodes along the path to be minimized. The most related work [4] was proposed to find out the optimal power with the constraint of a given bit-error probability, whereas our model is derived from a given frame-error probability. We present the results of simulations conducted to test the effectiveness of our proposed approach and compare the performances between ours and [4] based on the same constraint. The numerical results show that our algorithm achieves more accurate estimate of the transmit powers than [4].

1.2.2 Lifetime Maximization on WMSN

Efficient power control and lifetime maximization on a session are all important and correlative in WMSN. In the thesis, we also consider to resolve the maximization problem of session lifetime. Time-sensitive, non-interruptible streaming and multi-level quality are the typical characteristics of multimedia communication. In wireless networks, it is a challenge to relay media packets and keep media quality at an acceptable level. Prolonging route service time for multimedia session is one of the solutions to extend session lifetime. Usually, the requirements of extending route lifetime contradict the requirements of enhancing video quality. Therefore, we aim to ease the conflict in this dissertation. First of all, to quantify the multimedia quality, we refer to an end-to-end frame-loss probability as a visibility criterion. For example, the probability of 0.01 can represent that one frame is lost in average when 100 frames are transmitted. So, the QoS criterion serves as a good means for upper-layer applications to recover the lost multimedia frames. With respect to recovery schemes, numerous algorithms [25-29] were published in the past decade. In general, when using an appropriate recovery algorithm for multimedia applications, one can estimate how well the perception quality would be before a multimedia stream is initiated, and then specify an *e2e* error rate as the requirement. Again, with concerning how to sustain session quality, our objective is to select an optimal route that provides the longest service time to convey frames among all the possible routes to meet *e2e* QoS constraints.

To meet the above purpose, we consider a wireless routing protocol to collect some useful information for our design. When a multimedia session is initiated, the route-discovery packet (or route-request packet) is responsible for notifying intermediate nodes to reserve partial energy for this session. Thus, our proposed algorithms can find out an optimal route according to the information relating to individual links, such as reserved energy and link condition. Next, since scattered sensors in WMSN are usually deployed at a fixed place, link condition between two adjacent sensors simply depends on transmit power and noise density in the air; good linking means a link with low bit-error rate. Therefore, in order to increase route lifetime, we study method to either reserve more energy or reduce transmit power for relay nodes. As far as a relay node is concerned, if more energy is reserved for a certain session, fewer sessions are allowed to pass through the node. As a result, a new session may be easily rejected in its initial phase because relay nodes have no enough power for transmission. On the contrary, if we reduce the transmit power, bit error rate and frame-loss probability will quickly increase. Hence, our ultimate goal is to find the equilibrium for lifetime maximization between the requirements of low transmitting power and a satisfactory quality.

Motivated by [16], [17], we convert the lifetime maximization problem into a max-min composite formulation. Instead of searching all possible solutions for the composite formulation, we develop two novel algorithms to resolve. Hence, the lifetime maximization problem subject to a constraint of *e2e* frame-error probability can be quickly determined. The first algorithm, referred to as route-associated power management (RAPM), assumes that an initial transmit power is assigned to the relay nodes along the selected route. With an auxiliary condition on power management where identical transmit power is assigned to all intermediate nodes, we can quickly determine an optimal power level for the predefined QoS. This helps the computation-bounded sensor nodes obtain a longer lifetime. To obtain more accurate results, the second algorithm, referred to as link-associated power management (LAPM), takes all link conditions into account. In LAPM, all the individual powers can be determined and distributed to every intermediate node along the route. To validate our proposed algorithms, we perform theoretical analysis and simulation. From both analytical and simulation results, we observe that the results computed from analytical model are very close to a heuristic approach.

1.3 Organization of the Dissertation

The remainder of this dissertation is organized as follows. Chapter 2 reviews the related works on efficient power management and lifetime maximization. Chapter 3 introduces our system model and defines a QoS criterion. According to the model and QoS requirements, we propose an algorithm for route selection with efficient power consumption. In Chapter 4, we further study the lifetime problem and convert the problem into a maximization formulation. Two route selection algorithms are presented to cope with the lifetime maximization formulation. In Chapter 5, we give analytical results validated through simulation. Chapter 6 contains the concluding remarks.

Chapter 2 Survey of Literature

With sluggishly progressing on battery technology, power efficiency has obviously played an important role on wireless networking and wireless communications. Energy-efficient design requires a cross layer approach as power consumption is affected by all aspects of system design, ranging from silicon to applications. Authors in [37] summarize a comprehensive overview of recent advances in cross-layer design for energy-efficient wireless communications, especially focusing on system-based approaches toward energy optimal transmission and resource management across time, frequency, and spatial domains. This paper helps us to study the problems of power consumption in wireless networks. Moreover, the problem of how to maximize network lifetime has also become a significant topic on wireless networks. In this chapter, we classify recent works into two categories, power management and lifetime maximization.

2.1 Works on Power Management

Currently, to optimize the power usage while satisfying the quality-of-service (QoS) constraints is an important subject in wireless networking. Here, QoS constraint usually implies a threshold of packet loss rate, a tolerable level of packet delay, or the minimum throughput requirement. Previous works [3-10] have considered both power management and QoS issues in wireless environments.

2.1.1 Efficient Power on QoS Criterion

When sustaining transmission rate is the major QoS concern, schemes [8], [9], [11] associated with routing protocols have been proposed to jointly consider power usage and QoS constraint. For example, the authors in [8] developed a power-efficient routing algorithm to comply with a bandwidth-guaranteed provision in a TDMA-based CDMA system [3]. The algorithm can calculate adequate transmission powers and distribute them to the nodes along the path by adopting current routing protocols, Ad-hoc On-demand Distance Vector (AODV) and Dynamic Source Routing (DSR). Moreover, other power-saving issues (e.g., minimizing energy consumption on all routes) have been addressed in [9], [11]. To minimize all energy consumption on a wireless system under a specific utilization, the routing scheme in [11] can compute the appropriated bandwidths to all links by controlling every node’s power and re-routing each of the flows.

Apart from the consideration of QoS constraint on power management, some works [36], [44] focus on the adjustment of transmission power of wireless node. In [36], authors proposed a new adjustment method based on Fuzzy Control Theory, called FCTP, to properly adjust transmission power for saving energy.

2.1.2 Power Management on Link Scheduling

As the link capacity was mentioned in [32], the bit rate of a wireless link relies on how much the transmit power strength that a node uses. Therefore, connection quality of a wireless link may deteriorate due to co-channel interference caused by the fact that some of the nodes radiate excessive power by using the same frequency. Thus, proper link scheduling can improve power efficiency. Approaches [13-15] have resolved the problem by determining how much of the power to radiate and when to radiate it. To increase the utilization of a system, authors in [13], [14] proposed advanced schemes for link re-scheduling and power management on wireless networks.

In addition, a power distribution algorithm [15] was designed to adjust transmit power with jointly congestion condition; its simulation was run on a TCP Vegas-based network. Thus, the utilization of a wireless system can be increased by properly scheduling the link occupation and efficiently minimizing the power consumption.

Reducing power consumption in wireless network interfaces (WNI) is an effective way to prolong the battery lifetime of the mobile terminal. However, it takes some time for WNI to convert from the power-saving mode to the active mode, which brings many challenges for designing power-aware and QoS-aware service models. In [51], authors presented a novel power-conserving service model for streaming applications over wireless networks. At base station side, a new scheduling algorithm, called rate-based bulk scheduling (RBS), was designed to decide which flow should be served at which time. The mobile terminal relies on a proxy to buffer data so that the interface can sleep for a long time period to save power.

2.1.3 Power-aware Protocol

Recent studies have shown that it is of paramount importance to take into account the error-prone nature of wireless links when designing routing protocols for wireless networks. Therefore, some researches on power management focus on how to make routing protocol efficient since routing protocols can be designed to give better energy conservation performance.

In [12], authors proposed an energy-efficient reactive routing protocol by using the related factors, such as MAC layer requirement, transmitter power imbalance, route establishment, and route stability. Their analysis indicated that the proposed routing protocol not only provides efficient energy saving, but also improves link stability. In [35], enhanced service discovery in terms of efficiency was developed by piggybacking service information into routing messages. To encapsulate service information in existing Zone Routing Protocol, they proposed an extended protocol, E-ZRP. It is also important for multicast networking to save power consumption. In [38], a new protocol called Localized Energy-efficient Multicast Algorithm (LEMA) was proposed. LEMA is able to deal with the inherent errors of WSN by locally estimating the energy due to retransmissions. Thus, it is possible for LEMA to find energy-efficient paths to multiple destinations.

2.2 Works on Lifetime Maximization

Power managements in WSN are the foundation study of lifetime maximization. In existing works on power management, many previous research works [4] have been published to resolve the problems of economic power consumption, optimum routing determination, or flow control with QoS constraints in wireless multi-hop networks. Based on the research on power usage, many lifetime maximization problems have been published recently and can be classified into four subtopics as follows.

2.2.1 Topics on Network Lifetime

In recent literatures [20-22], [42, 43], not only do the authors provide efficient power controls, but also dedicate their works to extending network lifetime in system wide. Specifically, the authors in [20] considered adjusting both data rates and power allocation to maximize system lifetime. From routing point of view, the authors in [21] determined a routing algorithm to make system lifetime longer. Moreover, in [22], by considering both session flows and routing, lifetime maximization in system level was studied. In addition, with a time division multiple access (TDMA) system [23], the authors considered the joint optimal design on routing flows, link schedules, and link transmission powers for all active time slots so that system lifetime can be maximized.

Maximizing lifetime in wireless networks is usually an NP-complete problem, which can be fortunately solved by using either heuristic methods or other specific approaches. However, since it is not realistic for a wireless node to use heuristic method, alternative approaches were proposed. For example, Jantti and Kim in [20] proposed a lifetime determination method to adjust data rates and allocate appropriate power. By jointly minimizing the interference of power radiation and allocating transmission time slots of all nodes, they translated the multi-constraint problem into a Maximum Lifetime Routing Problem (MLRP), which is shown as a max-min problem. To resolve it, they presented an iterative algorithm associated with analysis.

Likewise, Hou *et al*. [22] resolved a maximization problem with other constraints. Since more relaying packets in a sensor may consume more powers for transmission, an optimal routing plan should be determined in order to make the lifetime of network system longer. Jointly considering flow routing and power consumption, maximization of network lifetime usually depends on how to figure out an optimal routing deployment for all flows in the system. Thus, such a complicated lifetime problem is usually formulated with linear programming so that they can propose a routing approach for a single-session flow and also prove it for multi-session routing. Facing similar issue in wireless networks, Cui *et al*. [21] converted the lifetime problem into a max-min fairness problem by means of utility factors. By adopting the results from [24], the utility-based formulation can be readily determined.

Authors in [43] proposed a cross-layer design approach for minimizing energy consumption and maximizing network lifetime for a multiple-source and single-sink (MSSS) WSN with constrained energy. The optimization problem for MSSS WSN can be formulated as a mixed integer convex optimization with the adoption of TDMA. This problem eventually becomes a convex problem by relaxing integer constraint on time slots. Therefore, impacts of data rate, link access, and routing are jointly taken into account in the optimization problem.

2.2.2 Topics on Multicasting

Different from the above works in the aspect of physical layer, researchers in [18], [44], [46] were devoted to enhancing power usage and maximizing lifetime in multicasting. An innovative algorithm in [18] was proposed to effectively determine transmit powers for maximizing lifetime in multicasting rather than heuristically solving the problem. In [44], authors reexamined the problem of maximizing multicast lifetime in wireless ad hoc networks under a transmitter-receiver power tradeoff (TRPT) model. In the model, the energy consumed for receiving a bit at each node is inversely proportional to the energy level at which the bit is transmitted. The authors proved the problem is NP-hard under the assumption of bounded and discrete power levels.

In addition, the joint design of physical layer, MAC layer, and network layer for multicast applications was considered in [46] to maximize lifetime with constrained energy. They basically investigated two energy efficient approaches, the minimum total energy and the min-max per node energy, to maximize network lifetime. They finally formulated the computing of multipath flow as a linear optimization problem.

2.2.3 Topics on Efficient Routing

Reducing energy consumption and extending lifetime are two important research subjects in wireless sensor networks (WSN). Many researches [30], [47], [50] have been involved in the joint issue of maximum lifetime and efficient routing. In [47], authors proposed an optimal scheme with mixed routing to optimize the lifetime of bottleneck nodes. The optimal problem was converted into a nonlinear programming problem, which was solved by a sub-gradient iterative algorithm. Their simulation has shown that network lifetime can be extended effectively.

Generally speaking, the main issue of WSNs is in efficiency, which aims to maximize network lifetime by means of minimizing energy consumption. Yet, delay is another important metric that should be considered. Therefore, authors in [50] proposed a new routing protocol for WSNs, called Pairs Energy Efficient Routing protocol (PEER), which uses dual power management by minimizing both the energy consumption and the transmission delay. In terms of energy consumption, network lifetime, and average delay, PEER has proved that it can perform better than LEACH (Low Energy Adaptive Clustering Hierarchy) protocol.

In addition, optimized routing (from source to sink) constitutes one of the key design issues on prolonging the lifetime of battery-limited sensor nodes in WSNs. In [30], authors explored the problem of optimal routing to select the next-hop node among multiple candidates by considering different cost functions, such as distance, remaining battery power, and link usage. Moreover, in this thesis, we further study lifetime maximization for optimizing individual route under end-to-end frame error constraints [16]. The problem of maximizing route lifetime for multimedia sessions will be formulated in Chapter 3.

2.2.4 Topics on Special Purposes

How to deploy wireless nodes with efficient power usage is an important problem in wireless sensor networks. Recently, many previous works [33], [34], [40], [41], [45] have focused on computing the location, link association, and energy allocation of wireless nodes. In [33], they considered a joint optimization problem for energy allocation and energy-aware routing, which is referred to as the joint optimization of energy allocation and routing problem (JOEARP). An exact algorithm was proposed to provide the optimum solution for the JOEARP. Likewise, in [40] and [41], authors investigated the deployment of wireless nodes in order to maximize the lifetime of a data flow.

Considering two-tier wireless sensor network architectures, authors in [34] proposed an optimal cluster association algorithm (OCAA) to maximize the overall network lifetime. The two-tier WSN consists of small sensor nodes (SNs), powerful application nodes (ANs), and base stations (BSs, or gateways). The SNs can capture, encode, and transmit relevant information to ANs, which then forward the combined information to BSs. In OCAA, it is assumed the locations of SNs, ANs, and BSs are all fixed and SNs are associated with appropriate ANs, such that network lifetime can be maximized and every node can acquire its required bandwidth.

Considering the strategy of energy assignment in a heterogeneous wireless sensor network, in [48], [49], authors focused on prolonging sensor network lifetime by properly assigning sensor nodes with initial energy. The proposed strategy of initial energy assignment (IEA) can be operated under two conditions, i.e., the total initial energy is limited or it is unlimited. Given the location and energy level of sensors, their goal was to optimize load balancing and prolong network lifetime. Simulations demonstrated that, if the operating condition is limited, a network by using the IEA strategy can live 92% longer than that by using the strategy of uniform initial energy assignment.

Regarding the precision of data gathered by sensor nodes, there is a tradeoff between data accuracy and energy consumption. To obtain an aggregated form of collecting data with precision guarantees, the precision constraint is partitioned and allocated to individual sensor nodes in a coordinated fashion. In [39], authors addressed a key idea to differentiate the precisions of data collected from different sensor nodes to balance their energy consumption. After analyzing the optimal precision allocation in terms of network lifetime, they proposed an adaptive scheme to dynamically adjust the precision constraints at sensor nodes. Additionally, they considered the topological relations among sensor nodes and the effect of network aggregation.

By considering the relay issue in an amplify-and-forward (AF) cooperative network, authors in [52] presented joint relay-selection and power-allocation strategies to prolong network lifetime. Three strategies on selective relaying were proposed based on the local channel state information (CSI) and the local residual energy information (REI) at each relay node. With a finite number of power levels, the energy dissipation process was modeled by finite-state Markov chains and the lifetime maximization problem was solved by dynamic programming.

Chapter 3 Minimization of Power Consumptions

Considering a system model to evaluate the above problem, we assume that a wireless system can distribute the mutual-orthogonal carrier frequencies to each node. The interference problems on co-channel and adjacent channels are nearly negligible and transmission collision will not occur in the air. Thus, the main interference on radio channel arises from white noise in the atmosphere, where the noise density within a unit interval is assumed to be time invariant but channel dependent. In addition, since each node is assumed to have sufficient buffer to store the relaying frames, frame dropping in the node can be neglected.

3.1 Model Description

The stability of multimedia flow in a wireless multi-hop network is subject to a route lifetime (also called session lifetime in our thesis), which usually refers to the service time that a multimedia session can continuously flow through a static route. In general, short service time could lead to poor video quality because occasional re-routing is initiated by the out-of-service node. However, long service time may not guarantee good quality because higher bit-error rate could occur in some wireless links. To sustain an acceptable quality and extend service time as longer as possible, we consider an *e2e* frame-error as QoS criterion, described in next section, and determine the longest lifetime as our ultimate objective. Unfortunately, both of the correlating operations on sustenance and extension are usually conflicting.

To comprehend the above contradiction, we take a brief example on multimedia streaming. Due to inevitable errors in wireless transmissions, each wireless link acting as a leaking pipe was filled with multimedia packets. Like glue to seal up, adjusting transmit power at a transmitter can reduce the leaking rate. For example, Figure 3-1 illustrates a multimedia flow streaming out from a source to its destination (called sink node) in a wireless multi-hop environment, where five multimedia frames are sent out through two wireless links. Because of noise interference, three frames were discarded during delivery and only two frames can arrive at the sink node. In this case, we can adjust transmit power against noise to recover the throughput, but the battery life will decay more quickly. To balance, correlation between power consumption and throughput is worthy of further studying.

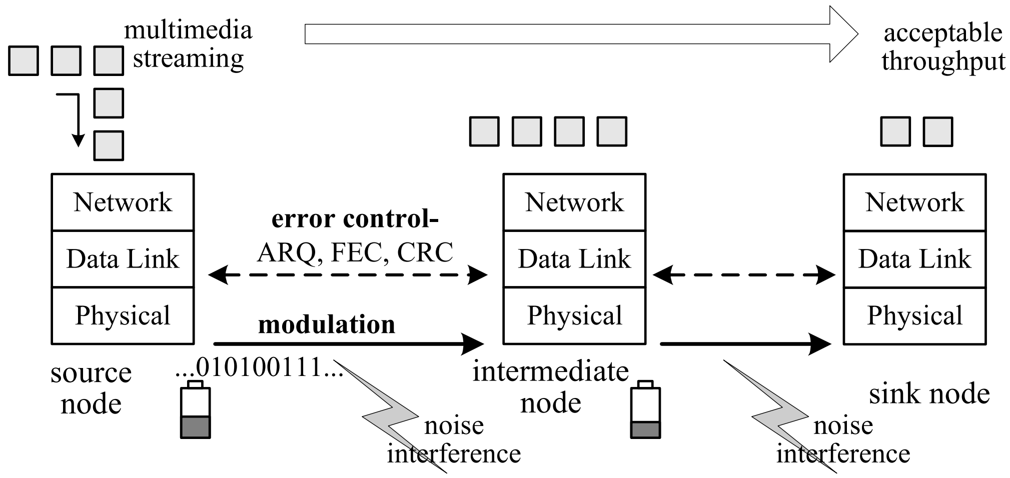


Figure 3-1: Multimedia streaming in a wireless multi-hop network.

An end-to-end throughput is highly related to data rate of a wireless link. In wireless communication, assume that transmit signal is attenuated with a communicating distance raised to a factor of path loss exponent *m*, where *m* is typically a constant between 2 and 4 [32]. Hence, the signal observed at a receiver is written as $\frac{\text{Transmit Power}}{\text{distance}^m}$. To measure frame loss in a wireless link, we can observe the data rate of the link. According to Shannon's theory [32], a maximum data rate in an error-free link (i.e., ideal case) from a node $j\text{-}1$ to its neighbor node j can be expressed by

$$R_{j-1,j} = W_{j-1} \log_2(1+\Gamma_{j-1,j}) \quad \text{in bps, and}$$

$$\Gamma_{j-1,j} = \frac{p_{j-1}}{\eta_{j-1,j} \cdot d_{j-1,j}^{m}}, \tag{3.1}$$

where W_{j-1} represents carrier bandwidth in Hz, p_{j-1} represents transmit power at node $j\text{-}1$, $d_{j-1,j}$ denotes distance in meter between the two nodes, and $\eta_{j-1,j}$ represents noise density in the wireless link.

From Eq. (3,1), the physical bit rate gradually increases with the increase of signal-to-noise ratio (SNR), which is strictly defined as a ratio of receiving signal over noise density. However, in a real world depending on the modulation characteristics of wireless channels, an error probability is associated with a bit rate; hence, error control schemes (ARQ, FEC, CRC, etc.) are widely used in data link layer as shown in Figure 3-1. To specify an *e2e* frame-error rate, we think about formulating frame-error rate of a wireless link and further derive an *e2e* frame-error rate of one session. Thus, the *e2e* frame-error rate can be viewed as QoS criterion, constrained by transmit power.

3.2 Definition of QoS Criterion

In the previous section, we realize that transmit power of wireless node and bit rate of wireless link are logarithmically proportional. Lower bit rate it is, worse QoS can be obtained. So, in reality, we should not sacrifice quality to save more power consumption. The main issue for us is how to qualify the quality. Thus, we will formulate the *e2e* frame-error probability as QoS criterion in this section. End-to-end frame-error rate may provide more accuracy than bit-error rate. Especially, frame error rate can be backward compatible, when we set frame size to

1 bit. Therefore *e2e* bit-error rate can be also applied.

First of all, consider a wireless link to derive a frame-error probability. When a packet is delivered from one node *j-1* to another node *j* via a radio channel, shown in Figure 3-1, the packet transmission error may occur with a certain probability relying on distance ($d_{j-1,j}$) between two nodes, transmit power (p_{j-1}), and noise level in the radio channel. If the SNR measured at a receiver exceeds a threshold (γ), the bit stream can be successfully received without errors. Otherwise some bits may be erroneous. In such a statistical model, *bit-error probability*, denoted by P_{be}, can be represented as a monotonically decreasing function of a received SNR, denoted by $\Gamma_{j-1,j}(\gamma)$. Therefore, we have

$$P_{be} = f\left(p_{j-1}, \eta_{j-1,j}, d_{j-1,j}\right) = f\left(p_j, \eta_{j-1,j}\right) = f\left(\Gamma_{j-1,j}(\gamma)\right), \tag{3.2}$$

where p_j represents received power level and $\eta_{j-1,j}$ represents noise density at the radio channel. Bit-error probability in most wireless communications, as described in [32], might be an exponential distribution or a Q-function[1]. For examples in various modulation technologies, P_{be} is equal to $\frac{1}{2}e^{-\Gamma(\gamma)}$ for DPSK, $\frac{1}{2}e^{-\frac{\Gamma(\gamma)}{2}}$ for FSK with non-coherent detection, and $Q\left(\sqrt{2\Gamma(\gamma)}\right)$ for BPSK and QPSK.

Equation (3.2) mainly specifies the behavior in the physical layer that emits each bit into a specific radio channel. To integrate adaptive power controls with QoS

---

[1] $Q(\alpha) = \frac{1}{2} - \frac{1}{2}erf\left(\frac{\alpha}{\sqrt{2}}\right)$, where $erf(\alpha) = \frac{2}{\sqrt{\pi}}\int_0^{\alpha} e^{-x^2}dx$

routing, we model the behaviors of the underlying data-link layer, including flow control schemes, as the dotted line shown in Figure 3-1. Assume that a frame, treated as unit length of transmission in data-link layer, consists of n bits. A *frame-error probability* (FEP), denoted by P_{fe}, can be computed without flow control process as follows.

$$P_{fe} = 1-(1-P_{be})^n = \sum_{i=1}^{n}(-1)^{i-1} \cdot C_i^n {P_{be}}^i. \tag{3.3}$$

However, a simplified equation in terms of $\Gamma_{j-1,j}(\gamma)$ (abbreviated as Γ) cannot be obtained from Eq. (3.3), especially in QPSK. Thus, solving a power minimization problem in the later section becomes a time-consuming task, unfortunately, which is not suitable for wireless node. To further explore the issue, we will find out a closed form to represent Eq. (3.3) even though the form is approximated.

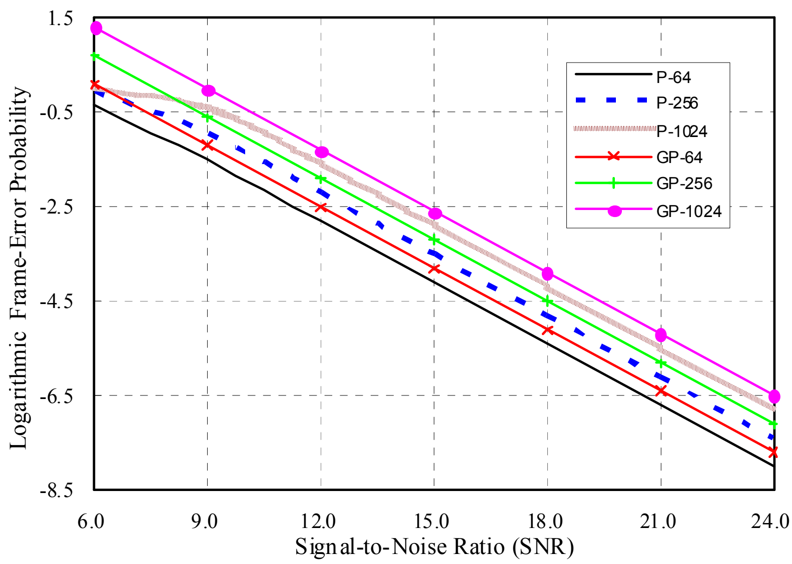
To obtain a generalized and concise form derived from Eq.(3.3), we first compute P_{fe} with the frame length of 64, 256, and 1024 bytes; then analyze P_{fe} in relation to Γ. The simulation adopts DPSK modulation in physical layer, but no flow control scheme in data link layer. The results in Figure 3-2 (a) depict the logarithmic P_{fe} versus different SNR levels. The three lines (P-64, P-256, and P-1024) indicate that the logarithmic FEPs are linearly decreasing with the increase of SNR. This demonstrates that the form in Eq.(3.3) approximates to an exponential distribution. Therefore, we define a generalized form of FEP in the following expression:

$$GP_{fe} = \phi_{j\text{-}1,j}\left(p_{j-1}\right) = Min\left(1,\ \frac{1}{2} n \cdot e^{-\alpha \cdot \Gamma^{\beta}}\right), \tag{3.4}$$

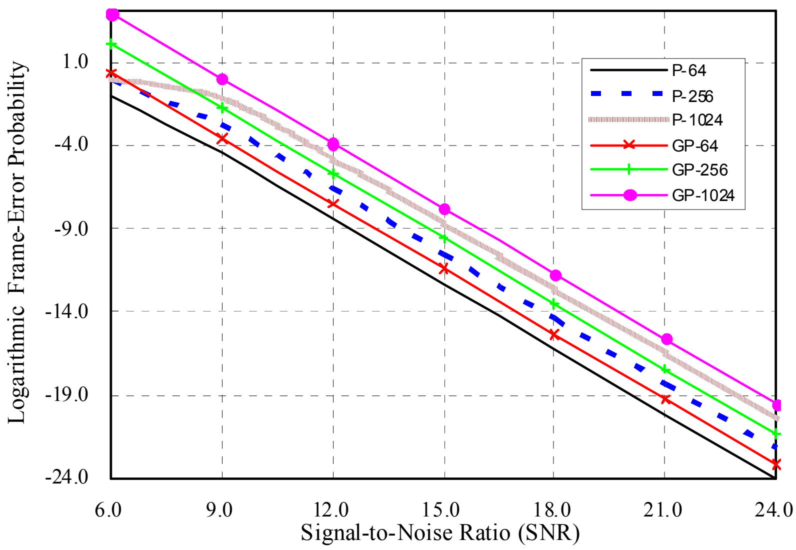
where (α, β) represents a pair of modulation factor. The (α, β) pair can now be set to (1, 1) for DPSK. To apply the general form to our model, we have one condition to comply with. Because the error probability is less than one, the inequality equation $\Gamma \geq \sqrt[\beta]{\frac{\ln n - \ln 2}{\alpha}}$ should be applied. For the precision of our system, SNR must be larger than the value of $\sqrt[\beta]{\frac{\ln n - \ln 2}{\alpha}}$.

To verification the precision of the general form, we compute GP_{fe} by applying the three frame lengths to Eq. (3.4). The values of GP_{fe} are also illustrated in Figure 3-2 (a) (see GP-64, GP-256, and GP-1024), quite close to those of P_{fe}. Similar simulations may be taken to choose the appropriate pairs for other modulations, such as (0.5, 1) for FSK, (1.414, 1) for QPSK, and (0.81, 1) for GMSK. In addition to low SNR condition, much more power will be wasted on transmission because sending frames may be readily interfered to become erroneous in a radio channel with a high FEP. Therefore, a minimum acceptable threshold to SNR must be defined in our system, namely SNR_{min_thres}. Once the SNR in a channel is detected below this threshold, we suggest this link be out of service, i.e., not allow using the radio channel. In the condition, when receiving a route-discovery message through this link, a wireless node should reject the request for raising power efficiency of entire wireless system.

Furthermore, consider error control scheme using in wireless systems. We assume that ARQ-N is adopted in wireless systems; then a frame-error probability can be expressed as GP_{fe}^{N}, where N represents retransmission times if one frame is lost or erroneous. The results of GP_{fe}^{N}, compared with Eq. (3.3), are shown in Figure 3-2 (b). Observe that the probabilities are much lower than those in Figure 3-2 (a). The ARQ scheme can outperform the accurate probability while a frame is transmitted by multiple times. However, more and more power could be consumed at a transmitter when the retransmission process is taken to correct an erroneous frame, especially in the worse case of a larger N. A suitable value to N is usually less than four in wireless systems. From the frame-error distribution, we define an average retransmission time as N_{avg} for each link. Thus, an average consumption of transmit power on each link can be computed as $p_{j-1} \cdot N_{avg}$.



(a) P_{fe} vs. SNR, and GP_{fe} vs. SNR without flow control



(b) P_{fe} vs. SNR, and GP_{fe} vs. SNR with ARQ-*3*

Figure 3-2: P_{fe} and GP_{fe} comparison for DSPK

3.3 Route Selection with Power Minimization

Issues regarding how to minimize power consumption and how to select a best route are discussed in this section. Although increasing power for transmission may obtain better link quality, unlimited power consumption is not acceptable in any wireless device. Hence we must define a *maximum transmit power*, which usually depends on the priority of a flow or the amount of remaining battery life. In other words, this limit is less critical when the flow is in high-priority transmission or this device is with high-power battery.

In the preceding section, we mention that Γ can be computed by measuring signal power and noise level at a receiver. An attenuation factor exists between receiving power and transmitting power because the radiating power is being lost in the air. Therefore we define *link gain* as a receiving to transmitting power ratio. Let us consider how to obtain an average link gain. In wireless networks, a beacon signal is periodically broadcasted at a specific power level to detect whether neighboring nodes are present or not. With referring to the signal, each of all neighbor nodes can calculate one link gain at an interval. When collecting the gains for a period, the receiver can obtain an average value. For instance in one cycle, if an upstream node $j\text{-}1$ broadcasts a beacon signal by a fixed transmit power, $P_{t\text{-}beacon}$, a downstream node j may evaluate the strength of the beacon signal, referred to as a receiving power, $P_{r\text{-}beacon}$. Hence the link gain at the two adjacent nodes ($j\text{-}1$, j) can be defined by

$$G_{j-1,j} = \frac{p_{r-beacon}}{p_{t-beacon}}. \qquad (3.5)$$

Note that since an upstream node periodically broadcasts beacon signal, a new link gain at a receiver is refreshed whenever a beacon signal is detected. The energy consumption on the task, which measures the link gain at a receiver, can be negligible as we compare it with the consumption on the task that forwards packets at a transmitter. In addition, for the sake of simplicity, we consider that link gain remains time-invariant (i.e., large scale as in [32]), so its expected value can be obtained. From Eq. (3.5), we define g_j as the average gain for the link ($j\text{-}1$, j).

Since link gain relates to the computation of power minimization, all of them must be delivered to the destination node while one route is being discovered. Some well-known routing protocols, such as the reactive routing AODV or DSR, have been widely employed today. Similar to AODV, we develop a general routing protocol in WSNs to collect all relative data for sink node to compute optimal powers. Then these calculated optimal powers are distributed back to the participants. Because a sink node is usually equipped with larger computational capability, it is assumed to have sufficient energy and battery life to handle the process. A source node will broadcast a Route-Discovery Request (RDREQ) packet to its neighbor nodes while it requires establishing one session to a sink node. Whenever an upstream node, *j-1*, receives the RDREQ packet, the node appends its maximum transmit power to this RDREQ packet. Likewise, when a downstream node, *j*, receive the RDREQ packet, it appends link gain, $\boldsymbol{g_j}$, along with white noise level, η_j, to this RDREQ packet. Once receiving the RDREQ packet, the sink node can obtain the groups of link gain and noise interference to optimize power consumption by using our approach, which will be described in the next section. Here, we formulate a set of link gain through *h* hops as $\boldsymbol{G} = (g_1, g_2, \ldots, g_\eta)$.

As far as power consumption on a node is concerned, the power is more significantly consumed in transmit operations (e.g., mainly power radiation) than that in receiving operations (e.g., signal detection). Our ultimate goal is to minimize the transmit power, because receiving consumption can be negligible. Therefore, a sink node may pick one route with least power consumption after computing all cost functions of power based on the retrieving information (i.e., link gain and noise level). Because a Route Reply (RREP) packet includes a list of the selected intermediate nodes, all optimal powers piggybacked by the RREP packet may be assigned to the participant nodes on the selected route. For clarification, a *route-calculation process* to minimize power consumption is designed and shown in Figure 3-3. Since our model is designed for on-demand (subject to e2e frame error rate), our proposed routing protocol can be suitable for the reactive protocols.

```
if ( Is_Source_Node )
{ // Set an initial end-to-end frame-error probability.
   Broadcasts request packets with a given quality level, QL.
}

if ( Is_Upstream_Node )
{ // Intermediate Nodes.
   Pt_max^{j-1} = Max_Power_TX( node j-1 );    // set max. transmit power.
   Attach( j-1, Pt_max^{j-1} );    // attach max. transmit power to the request packet.
}
else if ( Is_Downstream_Node )
{ // Intermediate Nodes.
   g_j = Calculate_Link_Gain( node j );
   η_j = Measure_Noise_Level( node j );
   Attach( j, g_j, η_j );    // attach data into the request packet.
}
else if ( Is_Sink_Node )
{
```

```
for all activated routes from source to sink
{
   Pt = Optimal_ Power( route R );    // calculate optimal transmit power.
   for ( i = 1 to h )    // h represents hop count on this route.
   {
      if ( ( p_r^i / η_i < SNR_min_thres) or (p_t^(i-1) > Pt_max^(i-1)) )
      {
         goto next_route;    // reject this route.
      }
   }
   Mark_Route( route R );    // set this route as a candidate.
   Sum( Pt );    // sum of power consumption.
}
Pick_Best_Route( );      // pick the least power consumption from candidates.
Assign_Process( );    // assign the optimal power to participants.
}
```

Figure 3-3: Pseudo-Codes for a Wireless Sensor Node.

3.4 Optimal Power Determination

As the previous section mentioned, white noise in our model usually interferes with a conveying frame, which may be lost or erroneous. Thus one wireless link can be associated with a frame-error rate, which infers this link's quality. When achieving a better quality during a session, mobile nodes could intuitively strengthen transmit power to increase the SNR in each link. Unfortunately, a drawback is that not all nodes on this route could conserve sufficient battery energy for a longer session so re-routing would frequently occur. To enhance power management, we define a *power cost* as the minimum power needed for a fixed quality in a wireless link. Here, a quality factor is defined to associate with a frame error probability. Accordingly, if a frame stream encounters multiple hops, the overall quality level on this route can be calculated by multiplying the correct frame probability of each link. Since the noise density and the link gain are time-invariant, their expected values in each link have been obtained in a randomly environment.

In order to formulate the power optimization, we classify all the parameters described above and divide them into the following two groups of parameters:

System-related parameters:

- (α, β): it indicates the signal modulation in a wireless system,
- n bits: frame size in data link layer,
- Maximum retransmission times: If no ARQ, $N = 1$; if ARQ is applied, $N \geq 2$.

Link-related parameters:

- Power density of channel noise (η): it is measured by a unit interval.
- Link gain ($\boldsymbol{g}$): it indicates the ratio of receiving power over transmit power,
- Transmit power (Pt): it is determined for a wireless device.

We can formulate the quality of service on a route to a power cost function with the constraint that a certain degree of end-to-end frame error probability should be met. Therefore, the cost to average power consumption on this route can be determined by $P_{avg} = \sum_{i=0}^{h-1}\left(Pt_i \cdot N_{avg}\right)$, where Pt is defined as transmit power and h is the hop count of the route. Because the average transmission times must be less than N, we obtain the inequality of power cost as follows.

$$N \cdot \sum_{i=0}^{h-1} Pt_i \geq P_{avg} \geq \sum_{i=0}^{h-1} Pt_i . \tag{3.6}$$

Next, the *end-to-end quality cost* that accumulates the individual quality cost per hop can be computed as

$$QC_{\mathrm{e2e}} = \prod_{i=1}^{h}\left(1 - GP_{fe_i}{}^{N}\right) . \tag{3.7}$$

With regard to the boundary of P_{avg} in Eq. (3.6), the average power can be minimized if we minimize the right term in Eq. (3.6). Meanwhile, the quality cost in Eq. (3.7) is unfortunately worsened by our power minimization. To this end, we attempt to optimize the average transmit power such that quality of connection is consistent under the given constraint.

Assuming that the end-to-end frame-accuracy probability, QL, is given and the (α, β) pair is set to (α, 1) for simplification. There exists at least one route from source node n_0 to sink node n_h in WSNs, where we consider an h-hop route passes through the intermediate nodes (n_1, n_2,…, n_{h-1}). Let $\boldsymbol{Pt} = \left(Pt_0, Pt_1, \ldots, Pt_{h-1}\right)$ be a set of transmit power for individual mobile node, i.e., the individual power must be taken in each frame delivery. Each element in the power set corresponds to a link set, $\boldsymbol{L} = \left(\ell_1, \ell_2, \ldots, \ell_h\right)$, where ℓ_i means a link from node n_{i-1} to n_i for $1 \leq i \leq h$.

Furthermore, a set of power density of white noise in each radio channel can be represented as $\eta = (\eta_1, \eta_2, \ldots, \eta_h)$. Thus, in order to find out the optimal power usage on this route, the problem of *end-to-end power management with QoS* can be specified as follows.

$$\underset{\boldsymbol{Pt}}{Min} \left(\sum_{i=0}^{h-1} Pt_i \right),$$

$$\text{subject to } QC_{\text{e2e}} = \prod_{i=1}^{h} \left(1 - GP_{fe_i}^{\ N}\right) = \prod_{i=1}^{h} \left(1 - C_n^N \cdot e^{-\frac{\alpha N g_i Pt_{i-1}}{\eta_i}}\right) \geq QL. \tag{3.8}$$

Eq. (3.8) can be solved by using the Lagrange method. A Lagrangian function of λ is shown as in Eq. (3.9).

$$J(\lambda) = Pt_{i-1} + \lambda \log\left(1 - C_n^N \cdot e^{-\frac{\alpha N g_i Pt_{i-1}}{\eta_i}}\right). \tag{3.9}$$

Letting $\frac{\partial J(\lambda)}{\partial \boldsymbol{Pt}} = 0$, we have

$$Pt_{i-1} = \frac{\eta_i}{\alpha \cdot Ng_i} \log\left[C_n^N \cdot (1 - \lambda x_i)\right], \quad \forall i = 1, 2, \ldots, h, \tag{3.10}$$

with the following condition,

$$\left[\prod_{i=1}^{h} \left(1 - \frac{1}{\lambda x_i}\right)\right]^{-1} = QL, \tag{3.11}$$

where $x_i = \frac{\alpha \cdot Ng_i}{\eta_i}$ represents the noise disturbance at one-watt transmit power in a corresponding link, ℓ_i. Although we can determine λ in Eq. (3.11) by using brute-force search, the high computational complexity is not suitable for real WSNs. Therefore, we propose an approximation approach to solving Eq. (3.11).

The basic strategy is to divide odd and even values of h for a polynomial analysis. By observing all possible values of λ from negative infinity to positive infinity, we conclude that every solution of λ for any of the odd values of h must reside in the two boundaries, $\lambda_1 < 0$ and $\lambda_2 > {x_h}^{-1}$, so that it can correspond to Eq. (3.11). Likewise, every solution for any of the even values of h must reside in the three boundaries, $\lambda_1 < 0$, $\lambda_2 \approx 0^+$, and $\lambda_3 > {x_h}^{-1}$. Consequently, any solution in Eq. (3.11) can only exist in this range, $\lambda < 0$, for any value of h with constraints, $x > 0$ and $\lambda x < 1$. This indicates that the term, $1 - \frac{1}{x_i \lambda}$, is always positive for $1 \le i \le h$ in Eq. (3.11). Thus, only one solution can exist in this range since Eq. (3.11) is a monotonically increasing function of λ. To simplify the multiplication of all terms, $1 - \frac{1}{x_i \lambda}$, we may calculate a mean for all x_i by using three different methods, i.e., harmonic mean, arithmetic mean, and geometric mean. However, large variance of all x_i may result in an inaccurate solution when we use the last two methods. Accordingly, instead of using arithmetic mean and geometric mean, let $\overline{\chi}$ be a harmonic mean of the elements (x_i). We can now determine λ by

$$\left[\overline{\chi} \cdot \left(1 - \frac{1}{\sqrt[h]{QL}} \right) \right]^{-1}, \qquad (3.12)$$

where the term $\overline{\chi}$ is given to $\frac{1}{\overline{\chi}} = \frac{\sum \frac{1}{x_i}}{h}$. Substituting this term for λ in Eq. (3.10), the individual transmit power is derived

$$Pt_{i-1} = \frac{\eta_i}{\alpha \cdot g_i}\left[\log\left(\frac{n}{2}\right) + \frac{1}{N}\log\left(1 + \frac{R_i \overline{PL_c}}{1-\overline{PL_c}}\right)\right], \quad \forall i = 1,2,\ldots,h, \tag{3.13}$$

where $R_i = \frac{x_i}{\overline{\chi}}$ represents the deviation of noise disturbance from average value on this route and $\overline{PL_c} = \sqrt[h]{QL}$ represents average frame-accuracy rate for each link. To simplify the parameters in Eq. (3.13), we define that $NG_i = \frac{\eta_i}{g_i}$ is a noise to link gain ratio in link ℓ_i, and $\overline{NG}$ is denoted as the mean of all noise-to-gain ratios on this route. Therefore, Equation (3.13) can be derived into an *NG* function given by

$$Pt_{i-1}(NG) = \frac{NG_i}{\alpha}\left[\log\left(\frac{n}{2}\right) + \frac{1}{N}\log\left(1 + \frac{\overline{PL_c}}{1-\overline{PL_c}} \cdot \frac{\overline{NG}}{NG_i}\right)\right], \quad \forall i = 1,2,\ldots,h. \tag{3.14}$$

If several paths are discovered from the source to the sink node, the optimal powers can readily be computed for every path by means of Eq. (3.14). The sink node picks the least power consumption among the candidates and distributes the transmit power by using the proposed routing protocol. Thus, the efficient power management in Eq. (3.14) can be applied to the selected node for frame transmission. Numerical analysis of optimal power determination will be presented in Section 5.1 and 5.2

3.5 Power Control for Multimedia

Consider MPEG coding in our model and we express how to use Eq. (3.8) to associate with multimedia quality in this section. An MPEG stream consists of three frame types (I, P, B-frame). We define packet size of I-frame, P-frame, and B-frame as *i_fs* bits, *p_fs* bits, and *b_fs* bits, respectively. According to Section 3.2, the frame size in data link layer is n bits. Therefore, the number of frames to transmit an I-frame packet, P-frame, and B-frame is $\left\lceil \frac{i\_fs}{n} \right\rceil$, $\left\lceil \frac{p\_fs}{n} \right\rceil$, and $\left\lceil \frac{b\_fs}{n} \right\rceil$, respectively.

In Section 3.4, the probability that a frame can successfully arrive to sink node is given to Eq. (3.7). We consider I-frame to transmit, so the probability that an I-frame packet can successfully arrive to sink node can be expressed to

$$I\_Ac = \left\{ \prod_{i=1}^{h} \left(1 - GP_{fe_i}^{\ N}\right) \right\}^{\left\lceil {i\_fs}/{n} \right\rceil}. \qquad (3.15)$$

The e2e probability can be used to QoS criterion of multimedia session. In order to find out an optimal power usage on this multimedia session, the problem of end-to-end power management with multimedia QoS can be specified as follows.

$$\underset{\boldsymbol{Pt}}{Min} \left(\sum_{i=0}^{h-1} Pt_i \right),$$

$$\text{subject to } \; I\_Ac \geq QL. \qquad (3.16)$$

To determine Eq. (3.16), we can obtain optimal power consumption associated with the quality constraint of I-frame delivery. Likewise, power management may be applied to P-frame and B-frame according to individual quality levels.

Chapter 4 Lifetime Maximization

4.1 How to Maximize Lifetime

4.1.1 System Description

In the previous chapter, we present how to discover a best route, consuming efficient power and also sustaining QoS. Next, how to discover a best route with maximum lifetime is our interest in this chapter. Recall to Figure 3-1, we illustrated a multimedia flow streaming out from a source to its destination (called sink node) in a wireless multi-hop environment. We continue to use this topology to specify the problem of lifetime maximization. In Section 3.2, we have generalized a frame error probability as in Eq. (3.4). Therefore, frame-error probability on a wireless link (*j-1*, *j*) can be rewritten to

$$\phi_{j-1,j}\left(p_{j-1}\right)=Min\left(1,\ \frac{1}{2}n\cdot e^{-\alpha\cdot\Gamma_{j-1,j}^{\beta}}\right), \tag{4.1}$$

where n denotes the length of a frame and (α, β) is a pair factor relating to channel modulation, e.g., BPSK or GMSK. By referring to the results in Section 3.2, the boundary of both factors is limited, i.e., $\alpha > 0$ and $0.5 < \beta \leq 1$ for diverse modulations. Specifically speaking, Eq. (4.1) represents an estimation of what percentage of a frame can be correctly received at next node and what percentage is lost. Therefore, to further compute the end-to-end frame-error as QoS criterion in a session, we can derive an *e2e* frame-error probability, from Eq. (4.1), as a function of transmit power.

Service time at a node is also highly related to frame loss in a wireless channel due to transmit power. Consider a wireless sensor network consisting of battery-limited nodes that are used to receive and forward frames. As far as a relay node is concerned, the service time which the node can provide relies on three factors: (i) reserved energy (denoted as E) from battery of the node, (ii) power (pt) for transmitting frames, and (iii) power (ρ) for receiving frames. Since the transmit power consumes much more than the receiving power in real environment, i.e., $pt \gg \rho$, the lifetime of the session at a relay node j can be approximated by

$$LT_j = E_j / (pt_j + \rho) \doteqdot E_j / pt_j. \quad (4.2)$$

In the phase of route discovery, the nodes that receive request messages may either reject establish request (i.e., E = 0) or allocate partial energy for relay service (i.e., E > 0). The strategy of energy allocation is based on the remaining battery life of the node and the in-progress tasks. According to Eq. (4.2), the smallest lifetime of all the relay nodes on a route is the service time where the route provides relay service for a session. Hence, we define the shortest service time as route lifetime, and express it in mathematical syntax below.

In networking, two nodes to set up a multimedia session can be defined as a pair. For example, pair (***s***, ***d***) represents an initiating node ***s*** connecting to a sink node $\boldsymbol{d}$. We assume that a route set, said **R** for pair ($\boldsymbol{s}$, $\boldsymbol{d}$), can be retrieved by adopting general routing protocols, and all the relay nodes on route i are listed to a node set, said $\mathbf{N}^{[i]}$. We can express the route lifetime within which a session can survive on the route i as

$$LT^{[i]} = \underset{j}{Min}\left\{LT_j^{[i]}\right\}, \ \forall j \in \mathbf{N}^{[i]}, \forall i \in \mathbf{R}. \tag{4.3}$$

Furthermore, let us denote $LT^{(s,\,d)}$ as an optimal lifetime for the session from node $\boldsymbol{s}$ to node $\boldsymbol{d}$. Hence, the optimal lifetime is to select the longest lifetime from the candidate routes, i.e.,

$$LT^{(s,d)} = \underset{i}{Max}\left\{LT^{[i]}\right\}, \ \forall i \in \mathbf{R}. \tag{4.4}$$

4.1.2 Problem Formulation

As the system model described above, the lifetime prolongation associated with QoS constraint can be expressed as a maximization problem. Consider a multimedia session, pair ($\boldsymbol{s}$, $\boldsymbol{d}$), and an *e2e* frame error probability as a criterion to keep multimedia quality at certain level. Assume ARQ scheme is adopted in the data link layer, and let N be a parameter of retransmission times when a frame is lost. Therefore, a frame-error probability in a wireless link (j-1, j) can be expressed as $\phi_{j-1,j}^{N}$, or equivalently, a frame-accuracy probability as $1-\phi_{j-1,j}^{N}$ from Eq. (4.1). Considering an end-to-end connection, the arrival rate of the frames at sink node is the product of the frame-accuracy probabilities for all links involved. Thus a cost formula, which can evaluate the receiving rate as QoS benchmark, is given by

$$Cost^{[i]} = \prod_{l} \left(1 - \phi_l^N\right), \ \forall l \in \text{all links involved on route } i, \ \forall i \in \mathbf{R}. \tag{4.5}$$

Implicit in Eq. (4.5) is the expense on achieving a certain quality, composed of the following three main variables: (i) individual transmit power of each relay node, (ii) noise density in involved links, and (iii) link distance. To be more specific, when it is required to achieve a fixed quality (i.e., given an *e2e* frame-error probability), the cost calculated from $Cost^{[i]}$ should not be paid less than the given price, otherwise, the quality cannot be satisfied. Yet, our objective is to minimize the QoS cost as lower as we can.

In addition to finding an economic cost, the trade-off problem of how a route can sustain a multimedia stream with a committed quality as longer as possible is also deserved our attention. To determine session lifetime on a certain route, we can integrate Eqs. (4.2) to (4.4) into a composite expression.

$$LT^{(s,d)} = \underset{i}{Max}\left\{ \underset{j}{Min}\left\{ LT_j^{[i]} \right\} \right\} = \underset{i}{Max}\left\{ \underset{j}{Min}\left\{ \frac{E_j^{[i]}}{pt_j^{[i]}} \right\} \right\}, \ \forall j \in \mathbf{N}^{[i]}, \forall i \in \mathbf{R}, \tag{4.6}$$

for pair (***s***, ***d***). With respect to wireless system, transmit power at each node should be restricted to a maximum value due to the interference effects on co-channel or on adjacent-channel. Let P_{max} denote the maximum transmit power in our system. By combining this max-min function and the cost constraint in Eq. (4.5), we yield the following complex formulation to resolve.

Maximum Session Lifetime Problem (MSLP)

Take Eq. (4.6), subject to

$$Cost^{[i]} \geq 1 - ER_{e2e}, \ \forall i \in \mathbf{R}, \tag{4.7}$$

for every candidate route i with a given *e2e* probability, and

$$0 < pt_j < P_{max}, \text{ and } 0 < \phi_{j-1,j} < 1, \ \forall j \in \mathbf{N}^{[i]}, \tag{4.8}$$

for every relay node j on the route i.

The problem of resolving the maximization is to determine an optimal set of individual transmit powers, $\{pt_j\}$, that the service to convey multimedia streams on a specific route may last as longer as possible. In Eq. (4.7), it is a requisite for us to hold the equals case because the low bound can meet the most efficient cost. Since the parameters (noise density and link distance) related to individual link conditions can be measured by signal detection schemes, they can be treated as static values. Based on the allocation strategy on a certain route, when a session initiator gives ER_{e2e}, we may determine many candidate sets of individual transmit powers, $\{pt_j\}$, that the inequality can be held and the conditions in Eq. (4.8) are also satisfied. Unfortunately, it is time consuming for us to find an optimal set from the candidate sets in Eq. (4.6) by using iterative-search method, called a heuristic solution. The related works [19][20][34] were also using iterative algorithms to solve min-max problems. According to the previous works, we propose a comparable strategy of optimal power selection to determine maximum session lifetime.

In the phase of route-discovering, a sink node will collect a list of reserved energy $\{E_j\}$ and noise density $\{\eta_j\}$ from routing packets. Using the gathered lists, the sink can compute individual route lifetimes and then pick a longest lifetime. Though, to solve the MSLP for sensor nodes is a challenge because it has scarce resources to compute. In past decades, researchers usually solve such lifetime maximization problems by using heuristic methods or specific approaches. Hence, in next sections, we propose two efficient approaches rather than using heuristic methods. One is called Route-Associated Power Management, and the other is called Link-Associated Power Management.

4.2 Route-Associated Power Management

Before describing our algorithm, let us specify variables and notations first. In a multi-hop wireless network, assume that noise density η on each link is individually measured by using signal detection schemes and distance d between two nodes is periodically calculated by adopting some location-aided routing protocols. Based on the assumptions, we may define a noise set as $\mathbf{\Psi} = \{\eta_{j-1,j}, \forall j \in \mathbf{N}\}$ and a distance set as $\mathbf{D}=\{d_{j-1,j}, \forall j \in \mathbf{N}\}$. In the phase of session initiation, a multimedia application issues a connection request with an *e2e* frame-error rate as QoS provision to its sink node. When the request is passing by every relay node during route discovery, it will carry information of noise density, link distance, and the allocated energy. Thus, besides noise set and distance set in the sink node, an energy set $\mathbf{E}=\{E_j, \forall j \in \mathbf{N}\}$ will also be grouped. As mentioned in the previous section, the determination of the longest lifetime can be expressed as the MSLP, composed of the information vectors. Unfortunately, it is a time-consuming task to determine the MSLP from Eqs. (4.6) to (4.8), which sometimes costs the sink node prohibitively. To simplify the problem on computing, we consider an auxiliary condition on power management, where an identical power will be utilized to all relay nodes for transmission. Furthermore, let us describe the condition for a certain route *i* using mathematical syntax as follows.

$$\exists\, pt^{[i]},\ i \in \mathbf{R} \text{ such that } pt_j = pt_k, \forall j,k \in \mathbf{N}^{[i]}. \tag{4.9}$$

The conditional approach to solve the MSLP with Eq. (4.9) is named as Route-Associated Power Management (RAPM). In order to reduce computation, it leads to unequal data rate for each link along the route when an identical power is adopted. However, the RAPM is an alternative solution for a network with low bit rate and limited computation.

Recall that the cost in Eq. (4.5) is composed of a transmit power vector $\{pt_1, pt_2 \ldots pt_h\}$ regarding a route i hopping h links. The cost function with an h-dimension vector can be mapped into one-dimension power variable when Eq. (4.9) is taken into account. Therefore, Eq. (4.7) can be rewritten as

$$Cost^{[i]}(p) = \prod_l (1-\phi_l^N) = \prod_l \; 1-(0.5n)^N \cdot e^{-\alpha \cdot N \left(\frac{pt}{\eta_l \cdot d_l^m} \right)^{\beta}} , \qquad (4.10)$$

$\eta \in \mathbf{\Psi}, d \in \mathbf{D}, \; \forall i \in \mathbf{R}.$

In Eq. (4.10), the constant in the exponent term, $\frac{\alpha \cdot N}{(\eta_l \cdot d_l^m)^{\beta}}$, is bounded to a minimum value of $\frac{\alpha \cdot N}{(\eta_{\max} \cdot d_{\max}^m)^{\beta}}$, where $\eta_{\max}$ denotes the strongest noise density of the involved links and $d_{\max}$ is the farthest distance. Thus, the inequality of the cost function can be deduced to

$$Cost^{[i]}(p) = \prod_l 1-(0.5n)^N \cdot e^{-\alpha \cdot N \left(\frac{pt}{\eta_l \cdot d_l^m} \right)^{\beta}} \geq$$

$$\prod_l 1-(0.5n)^N \cdot e^{-\alpha \cdot N \left(\frac{pt}{\eta_{\max} \cdot d_{\max}^m} \right)^{\beta}} = \left(1-(0.5n)^N \cdot e^{-\alpha \cdot N \left(\frac{pt}{\eta_{\max} \cdot d_{\max}^m} \right)^{\beta}} \right)^h . \qquad (4.11)$$

Compared with the constraint in Eq. (4.7), the right term of the inequality in Eq. (4.11) must be larger than the given value (i.e., $1-ER_{e2e}$). If so, the left term of the inequality will be always larger than $1-ER_{e2e}$, which makes the QoS provision to be satisfied. By holding the equality, a minimum transmit power on a certain route *i* can be determined as

$$pt^{[i]} \geq \eta_{\max} d_{\max}^{m} \left(\frac{N \cdot \log(0.5n) - \log(1-Q)}{\alpha \cdot N} \right)^{1/\beta} = \frac{\eta_{\max} d_{\max}^{m}}{\sqrt[\beta]{\alpha \cdot N}} \cdot \left(\log \frac{(0.5n)^{N}}{1-Q} \right)^{1/\beta}, \tag{4.12}$$

where Q represents $\sqrt[h]{1-ER_{e2e}}$. Integrating the auxiliary condition in Eq. (4.9) with Eq. (4.6), we can simplify the optimal lifetime into

$$LT^{[i]} = \underset{j}{Min}\left\{ \frac{E_{j}^{[i]}}{pt^{[i]}} \right\} = \frac{E_{\min}^{[i]}}{Min\left\{pt^{[i]}\right\}}, \ \forall j \in \mathbf{N}^{[i]}, \tag{4.13}$$

where $E_{\min}$ is the minimum element in **E**.

By observing Eq. (4.12), we use its lower bound as the minimum transmit power in a route *i*. Because $E_{\min}$ is a static number by allocation strategy, the lifetime of the route *i* can be easily determined by substituting the minimum transmit power into Eq. (4.13). Moreover, noise density is assumed to be time invariant and it is consistent in μ. Since small area network is assumed, path loss exponent *m* can be set to 2. With these assumptions along with the minimum transmit power, the lifetime in a route *i* can be expressed as

$$LT^{[i]} = \frac{E_{\min}^{[i]}}{\mu d_{\max}^{2}} \cdot \sqrt[\beta]{\frac{\alpha \cdot N}{N \cdot \log(0.5n) - \log(1-Q)}}. \tag{4.14}$$

With respect to Eq. (4.14), we can divide all of the variables into the following three groups: (i) system-related parameters (*N*, *n*, α, and β), (ii) route-related parameters ($E_{\min}$, $d_{\max}$, μ, and link hop h), and (iii) user-specific parameter (ER_{e2e}). The system-related parameters are always given by system constructors in building up system network, so route lifetime varies as the route-related parameters. In terms of implementation, Eq. (4.14) needs to take β-root and logarithms operations; it is not realistic and straightforward for power-limited devices, e.g., wireless microphone, to compute these complex operations. Although we may use lookup table instead of operating logarithmic calculations, the lookup operation to perform β-root still costs prohibitively in a resource-limited node. For instance, in a situation where 10 routes or more are sought, the burden at sink node is highly exhaustive to perform β-root operations at least 10 times. To this end, further interest to us is to rapidly judge which route can provide the longest service time. This can be done by telling sink node what its lifetime and transmit power are if the route was chosen. To realize the idea, we consider using similarity function to obtain an approximate equation that does not include the β-root term. This approximate equation, called judgment factor, can help us to judge which route is the best by quickly computing its lifetime and power. The following lemma tries to take the β-root term in Eq. (4.14) away by transforming it into a logarithm-related expression.

Lemma 4.1: Given a positive integer h, a Z-th root function of h represents $f(h)=\sqrt[Z]{X-\log(1-\sqrt[h]{Y})}$, where ($X$, Y, Z) are positive constants with the limits on $0 < Y < 1$ and $0.5 < Z \leq 1$. The function is increasing and it can be approximated to $Z^{1}\log(h) + Const$, where $Const$ is a composite constant relating to (X, Y, Z).

Proof: Considering two positive integers h_1 and h_2, we assume $h_1 < h_2$. Because Y is a positive fraction but blow one (i.e., $0 < Y < 1$), we have the inequality $Y < \sqrt[h_1]{Y} < \sqrt[h_2]{Y} < 1$ when taking h-root operation. Then, a log inequality $\log(1-\sqrt[h_2]{Y}) < \log(1-\sqrt[h_1]{Y}) < 0$ is also held. Put the above inequality into h-function, and $\sqrt[Z]{X} < f(h_1) < f(h_2)$ can be achieved. Consequently, it is proven that $f(h)$ is increasing.

As far as an integer h is concerned, the root term, $\sqrt[h]{Y}$, is an increasing series, i.e., $\{Y^{1}, Y^{1/2}, Y^{1/3}, \ldots, Y^{1/h}\}$. Its maximum value will converge to one when h tends toward infinite. Thus, let us approximate the series by $1-\frac{Y}{h}$. Substituting the approximation into $f(h)$, a similarity function (denoted as $\overline{f}(h)$) is derived.

$$\overline{f}(h) = \sqrt[Z]{X - \log\left(1-(1-Y/h)\right)}$$

$$= \sqrt[Z]{X - \log Y + \log h}$$

$$= \sqrt[Z]{K + \log h} = \sqrt[Z]{\log h \cdot 10^{K}}$$

$$\geq \log \sqrt[Z]{h \cdot 10^{K}} = Z^{-1}\left(K + \log h\right).$$

Here, let us define K to be $X - \log(Y)$. Because Y is less than one, we know that K is always positive. As a result, the similarity function is bounded to $Z^{1}(K + \log h)$, and the function $f(h)$ will be proportional to $Z^{-1}\log(h)+Const$ with Z nearing to one. ■

Proposition 4.1: Suppose that several routes have been discovered for a session. According to the RAPM scheme, each transmit power of the routes can be proportionally near to $Pwr=\frac{\eta_{\max}d_{\max}^2\cdot(\log h+K)}{\beta\cdot\sqrt[\beta]{\alpha N}}$, where K is a positive constant. Likewise, each lifetime of the routes is proportionally approximated to a judgment factor, $RT=\frac{E_{\min}}{Pwr}$. Therefore, a coarse decision can be made to pick the longest lifetime from these routes.

Proof: In Eq. (4.14), we consider the denominator term, $\sqrt[\beta]{N\log(0.5n)-\log\left(1-\sqrt[h]{1-ER_{e2e}}\right)}$. Let X be $N\log(0.5n)$, Y be $(1-ER_{e2e})$, and Z be β. According to the result in Lemma 4.1, the term can be approximated to $\beta^{-1}[\log(h)+K]$ as an h-function, where K is a positive constant relating to N, n, β and ER_{e2e}. Substituting the approximation into Eq. (4.12), we thus obtain a factor Pwr, proportional to the transmit power pt, i.e., $pt\propto Pwr=\frac{\eta_{\max}d_{\max}^2\cdot(\log h+K)}{\beta\cdot\sqrt[\beta]{\alpha N}}$. Similar to Eq. (4.14), the route lifetime is approximated to judgment factor, RT. As a result, the approximations will help us to rapidly select a suitable route by comparing the factors of all the candidate routes. ■

4.3 Link-Associated Power Management

Since solving the MSLP in a sink is a time-consuming task, we propose the RAPM method for computation-restricted nodes. The RAPM gives light computation but rough results. However, more accurate results are still needed for sophisticated nodes, e.g., wireless camcorder. Regarding the MSLP without auxiliary condition, its heuristic results by iteratively searching the satisfactory solutions are more precise but time-consuming. To effectively obtain its ultimate solution, we propose a new approach.

Let us take an example on an h-hop route that has a power set with h elements; there are at least h multiplication operations to Eq. (4.7) for iteration. For iterative search, if each element has τ possible power levels to calculate the cost, the number of all possible power sets drastically increases to τ^h. As a result, the complexity to find an optimal solution for the MSLP rises to τ^h operations or more. In contrast to the RAPM, this proposed scheme resolves the MSLP without concerning auxiliary condition and is named as Link-Associated Power Management (LAPM). Compared to the heuristic method, a convergence algorithm is proposed below to reduce the complexity and find an optimal solution as follows.

To specifically explain our approach, we consider a certain route and determine its lifetime. If there are several routes discovered for pair (***s***, ***d***), similar operations are applied to compute other route lifetimes. The results will help sink node $\boldsymbol{d}$ to choose the longest lifetime by using route-selection strategy. We address the lemmas below prior to presenting our algorithm.

Lemma 4.2: Given a frame error probability $\psi^N(p)$ with a retransmission parameter, the accuracy probability can be expressed as

$$\boldsymbol{Ac}(p) = 1 - \psi^N(p). \tag{4.15}$$

The above expression is an increasing concave function which increases as the transmit power p increases. Thus, the QoS cost in Eq. (4.5) is a product of the increasing-concave and positive probabilities. Considering a fixed expense of QoS provision, if one of the terms of accuracy probabilities is increased (or decreased), other terms of accuracy probabilities must be decreased (or increased) for keeping the cost unchanged.

Proof: By differentiating Eq. (4.15), we have

$$\boldsymbol{Ac'}(p) = Gp^{\beta-1} \cdot \phi^N(p) > 0 \text{ and } \boldsymbol{Ac''}(p) = [(\beta-1)p^{-1} - Gp^{\beta-1}] \cdot \boldsymbol{Ac'} < 0,$$

where $G = \dfrac{\alpha\beta N}{\eta^{\beta} \cdot d^{m\beta}}$ is a positive constant. According to the calculus on derivatives and graphing, it can be proven that Eq. (4.15) is a strictly increasing concave function. Hence, the QoS cost is composed of multiple increasing functions. Under the condition of fixing a cost, when any one of the accuracy probabilities in Eq. (4.5) is increased, we have to depress other accuracy probabilities to compensate the raised cost. ■

Based on the statement in Lemma 4.2, we summarize that the QoS cost will certainly increase if any one of individual transmit powers is boosted; otherwise, the cost will lessen. By the summary, when a predefined expense is given, we have the following lemma to obtain a valid power set at fixed cost.

Lemma 4.3: For the cost function in Eq. (4.5), i.e., $Cost^{[i]}$ for a certain route i, there exists at least one set of individual transmit power that can satisfy the condition of $Cost^{[i]} = 1 - ER_{e2e}$.

Proof: Assume that h is defined as hop count of the route i. By dividing $(1 - ER_{e2e})$ into h multiplicands in equal parts, we conclude that one transmit power p_{j-1} for a certain link (j-1, j) can be determined in the condition of $1-\phi_{j-1,j}^{N}(p)=\sqrt[h]{1-ER_{e2e}}$.

By applying the above conclusion to other links, thus, a power set $\mathbf{P}^{[i]} = \{p_1, p_2, \ldots, p_h\}$ for the route i can be obtained so that the aggregated cost is proven to be $(1 - ER_{e2e})$. So, at least one solution exists. ■

Summarizing Lemma 4.2 and Lemma 4.3, we realize that there are infinite sets that may converge to the same cost. For example for a 3-hop route constraining a cost of 0.9, a set of $\left\{\sqrt[3]{0.9},\sqrt[3]{0.9},\sqrt[3]{0.9}\approx 0.9655\right\}$ is the solution for $Cost^{[i]}$.

Nevertheless, the set of $\{0.96, \sqrt[3]{0.9}, 0.971\}$ can satisfy the cost too. By fine tuning the elements, we can find a great number of sets as a solution. Our ultimate goal is to efficiently determine an optimal set rather than heuristically. According to Eq. (4.2), the cost function of a power vector can be converted to a lifetime-based function of an energy set. The conversion will help us to easily find an optimal solution for route lifetime. To summarize above discussions, we propose a convergence method, called Route Lifetime Maximization Algorithm, to solve the MSLP. Note that the algorithm is operated at a sink node.

Route Lifetime Maximization (RLM) Algorithm

Step 0 (initial state):

For an h-hop route, let $\mathbf{P}=\{p_1, p_2,\ldots, p_h\}$ be a transmit power set whose elements are determined from Lemma 4.3. All of the reserved energies are listed to **E**. By taking the division of **E** by **P**, we may compute $\mathbf{T}=\{t_1, t_2,\ldots, t_h\}$ as a route lifetime set.

Let us sort the lifetime set with ascending order. The same arrangements are also done to the power set **P** and the energy set **E**. Thus, we have three ordered sets as initial values. Using an iterative algorithm to search the optimal point, let us define a time slice (denoted as δ) as step size for adjusting lifetime element.

Step 1 (adjusting lifetime):

- Adding the first element in the sorted set by δ, i.e., $\boldsymbol{t_{min}}=\boldsymbol{t_1}+\delta$, we gradually shrink the time of the last element until the cost is satisfied. Thus, the new determined element is named as $\boldsymbol{t_{max}}$.

- Compute the corresponding powers, and go to next step.

Step 2 (examining conditions):

- If either of the following two conditions is met: (i) when t_{max} is smaller than t_{min}, and (ii) no t_{max} can be determined, then t_{min} is the solution for route lifetime and the procedure is terminated.
- Otherwise, go to next step.

Step 3 (sorting elements):

- After sorting other elements with both the new values (t_{min}, t_{max}) in ascending order, we may get a new list as **T'**. The same arrangements are also done to the power set and the energy set.
- Go to next step.

Step 4 (convergence):

- If the subtraction of the first element (t'_1) from the last element (t'_{last}) in the ordered set **T'** is not larger than δ (i.e., $t'_{last} - t'_1 \leq \delta$), then the first element is the solution for route lifetime and the procedure is terminated.
- Otherwise, return to Step 1. □

In order to solve the route lifetime associated with a fixed cost, we cite the result of Lemma 4.2 to the Step 2 in the above algorithm. Regarding the principle of an increasing function, when the minimum time element is slightly increased by δ and the others remain unchanged, we have to decrease the maximum one until the determined time can make the cost identical. Without asserting Lemma 4.2, it is not guaranteed that the decrease operations can determine a proper time for convergence. In Step 3, while sorting all time elements, we arrange the elements in power set **P** in accordance with the order of time element exchanges. When the lifetime difference between maximum and minimum is smaller than the step size δ, the convergence process stops. In the above algorithm, two break points, examined in Step 2 and Step 4, are considered to terminate the convergence procedure. Therefore, we have a corollary to demonstrate the tradeoff between iteration complexity and result accuracy in the RLM algorithm.

Corollary 4.1: In the RLM algorithm, iteration complexity and result accuracy rely on time slice, δ. When a small value is given to δ, a higher accuracy can be achieved but time-consuming. Therefore, the iteration times to search optimal lifetime is at most $\left\lceil \frac{t_{last} - t_{first}}{\delta} \right\rceil$, where t_{last} is the maximum element in an initial set and t_{first} is the minimum one.

Proof: Because each of the multiplicand terms in cost equation is a one-to-one mapping function, the convergence range is restricted to $[t_{first}, t_{last}]$. Within the range, every step toward an optimal point is the step size δ, so iteration times for convergence can be estimated up to $\left\lceil \frac{t_{last} - t_{first}}{\delta} \right\rceil$. ■

To more perceive the process in the RLM algorithm, we give a numerical example as follows. Assuming that a string topology with 5 nodes, we illustrate how to discover the optimal solution by giving an example below.

Example: Assume that $N=1$, $n=1024$ bits, $(\alpha, \beta)=(1, 1)$, $\eta=1$ mW, and $ER_{e2e}=$

0.1. Let the adjacent distance of the nodes be 1 meter, and a set of reserved energy be given to $\boldsymbol{E}=\{5.0, 4.8, 5.2, 4.9\}$ mWhr. By using Lemma 4.3, we obtain a power set $\mathbf{P}=\{9.89, 9.89, 9.89, 9.89\}$ mW, corresponding to the lifetime set $\mathbf{T}=\{0.506, 0.485, 0.526, 0.495\}$ in hours for triggering the iteration.

Let us choose $\delta=0.005$ hr as time slice and sort the lifetime set in ascending order. Hence, we have the ordered set, i.e., $\{t_2, t_4, t_1, t_3\}=\{0.485, 0.495, 0.506, 0.526\}$. The detailed procedures to recursive searching are demonstrated below.

The 1st round:

In Step 1, after adding t_2 by δ and determining t_3, we have a new time set, i.e., $\{t_2, t_4, t_1, t_3\}=\{0.49, 0.495, 0.506, 0.521\}$. No termination occurs after Step 2 and 4 are examined, so next round is required.

The 2nd round:

In Step 1, after adding t_2 by δ and determining t_3, we have a new time set, i.e., $\{t_2, t_4, t_1, t_3\}=\{0.495, 0.495, 0.506, 0.514\}$. Since no termination occurs in examining Steps 2 and 4, go to next round.

The 3rd round:

In Step 1, after adding t_2 by δ and determining t_3, we have a new time set, i.e., $\{t_2, t_4, t_1, t_3\}=\{0.500, 0.495, 0.506, 0.505\}$. Both of the conditions are not met in Step 2. However, we place the elements in ascending sequence so that the ordered set, i.e., $\{t_4, t_2, t_3, t_1\}=\{0.495, 0.500, 0.505, 0.506\}$ can be obtained. Since no termination occurs in Step 4, go to next round.

The 4th round:

In Step 1, after adding $\boldsymbol{t_4}$ by δ and determining $\boldsymbol{t_1}$, we have a new time set, i.e., $\{\boldsymbol{t_4}, \boldsymbol{t_2}, \boldsymbol{t_3}, \boldsymbol{t_1}\} = \{0.500, 0.500, 0.505, 0.501\}$. Both of the conditions are not met in Step 2. In Step 3, we sort the elements in ascending order and have $\{\boldsymbol{t_4}, \boldsymbol{t_2}, \boldsymbol{t_1}, \boldsymbol{t_3}\} = \{0.500, 0.500, 0.501, 0.505\}$. In Step 4, because $(\boldsymbol{t_3} - \boldsymbol{t_4})$ is not larger than step size, the iterative process is terminated and $\boldsymbol{t_4}$ is the solution.

In the end, the ultimate route lifetime is 0.5 hr and the transmit powers of {9.98, 9.6, 10.3, 9.8} mW can also be determined. In this example, 4 rounds are taken to achieve the convergence. Hence the consequence conforms to Corollary 4.1. □

Note that we rapidly compute a route lifetime by using the proposed algorithm. If a routing protocol discovers several routes, the following strategy is needed to select an optimal route.

Route-Selection Strategy: When receiving the QoS requirement and all of the route information from the relay nodes, a sink node starts to compute each lifetime by using the RLM algorithm. Thus, the sink selects the longest lifetime and then returns a reply packet that includes the list of individual transmit powers for establishing the selected route.

To explore a durable route lifetime in case of the MLSP, we have to adopt the above strategy with the RLM algorithm because the computing processes may be more competitive to the heuristic method. In general, the LAPM scheme can be employed to the wireless nodes that are affordable for large computations. Furthermore, to gain a flexible design, we can sacrifice some accuracy to achieve longer lifetime. To this end, we suggest a hybrid method that can fully utilize both the advantages of RAPM and LAPM. To be more specific, by Proposition 4.1, we can select a route with the longest lifetime followed by using the RLM algorithm on the selected route. Hence, the RLM operates only once in selecting a route from multiple routes.

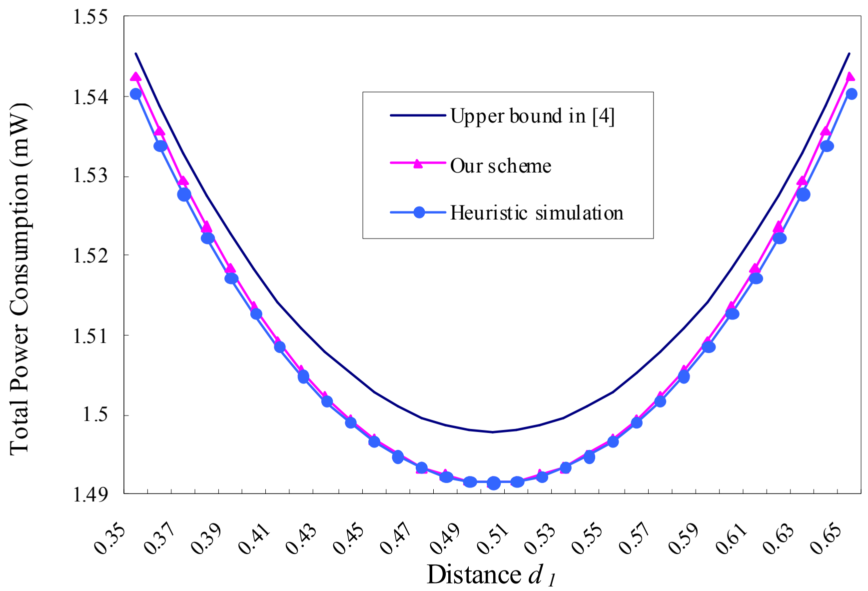
Chapter 5 Numerical Analysis

5.1 Analysis of Power Control

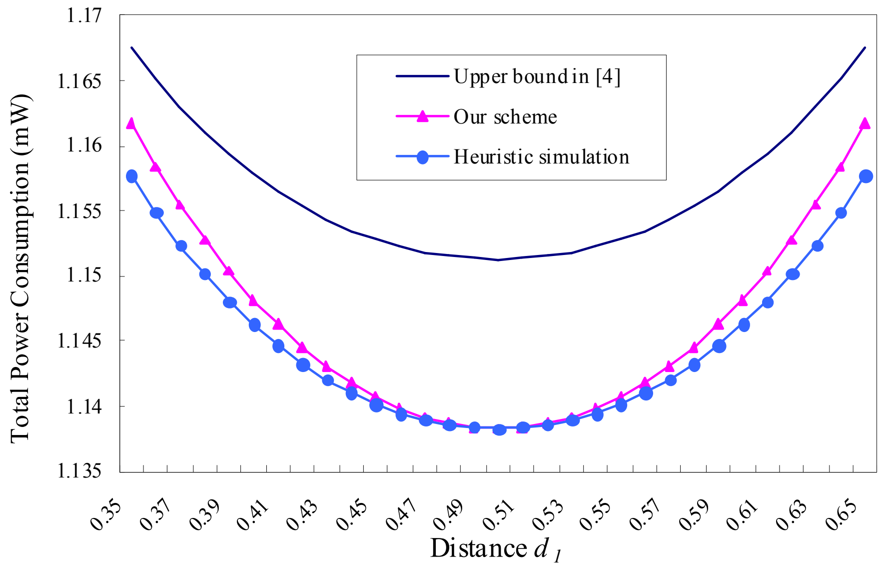
5.1.1 Comparison with a Previous Work

The numerical experiments on power consumption were performed in this section. With regard to the quality constraint, a fixed bit-error probability can be satisfied in our scheme when $n = 1$. A somewhat similar work, but without considering flow control mechanism was published in [4], where they considered an approach of seeking the upper and lower bound for the power minimization problem. The same topology used in [4] was adopted for an objective comparison with our approach derived from Eq. (3.14). In addition, the distance constraints, $0 \le d_1 \le 1$, $0 \le d_2 \le 1$, and $d_1+d_2 \ge 1$, were also taken into account.

The resulting power consumption was shown in Figure 5-1 (a) with the end-to-end bit-error probability of 0.05 and in Figure 5-1 (b) with that of 0.1. The total power consumption determined by our approach is roughly 1.138 mW at $d_1 = 0.5$ in Figure 5-1 (a), whereas that determined by his upper bound is around 1.151 mW. It is observed that a significant gap exists between his approach and ours in Figure 5-1 (b). As illustrated in the figures, our scheme can more precisely determine the optimal power based on the same constraints. Moreover, the outcome indicates that our analytical values for $d_1 = 0.5$ derived from Eq. (3.14) are significantly closer to the results determined by a heuristic method, which iteratively finds the solution by using *MATLAB* simulator. As a result, our closed form can provide a more accurate solution for rapidly computing the optimal power.



(a) Bit error probability = 0.05



(b) Bit error probability = 0.1

Figure 5-1: Comparisons in total power consumption.

5.1.2 Study of Different Parameters

Numerical results were examined for the power-consuming effects of the parameters: *NG* ratio and retransmission times. Table 5-1 specifies a 5-hop path with an end-to-end *QL* = 0.8, *n* = 128-byte, and using DPSK modulation (i.e., α = 1, β = 1). In addition, white noise strength in each link and link gain per hop were also given. From the table settings, the *NG* ratio of each hop can be computed to be 38.2, 30.8, 22.9, 28, and 40, respectively.

Table 5-1: Given Parameters for Power Minimization

n	128 bytes (1024-bit)					
(α, β) pair	(1, 1) for DPSK					
QL	0.8					
Pass Through Nodes	S	N1	N2	N3	N4	Sink
Noise Strength (μW)	-	0.65	0.40	0.55	0.35	0.70
Link Gain	-	0.017	0.013	0.024	0.0125	0.0175

First, we investigated the performance on the individual power with various *NG* ratios. The optimal power in the source node was examined by varying the *NG* ratio of the first hop, and the result is shown in Figure 5-2. In this figure, the optimal power consumes to each frame delivery in proportion to its *NG* ratio with regardless of retransmission times. More interestingly, the transmit power with *N* = 1 is needed more than that with *N* = 8 at a fixed *NG* ratio. That is because the frame error probability at ARQ-8 is much lower. Although the power at higher *N* consumes less to delivery every frame in principle, the average power consumption may not comply with the above observation to deliver an accurate frame. Therefore, we were interested in summing the average of transmit power of each node where the quality level was given by 0.9, 0.8, 0.7, and 0.6, respectively.

Using the parameters (i.e., n, α, β, and QL) given in Table 1, we assumed that the NG ratio was 40.0 to each link. The average power consumption, $P_t{\cdot}N_{avg}$, is shown in Figure 5-3. We can observe that the average consumption on the aggregate power almost increases with the retransmission times. However, the best value of N is 2 for the QL of 0.9 and 0.8. As a result, if an inappropriate value is set to N, the aggregate power consumption will not be efficiently reduced on re-transmitting the erroneous frames. Consequently, the best retransmission times in our scheme could be less than 4 for high-quality transmission.

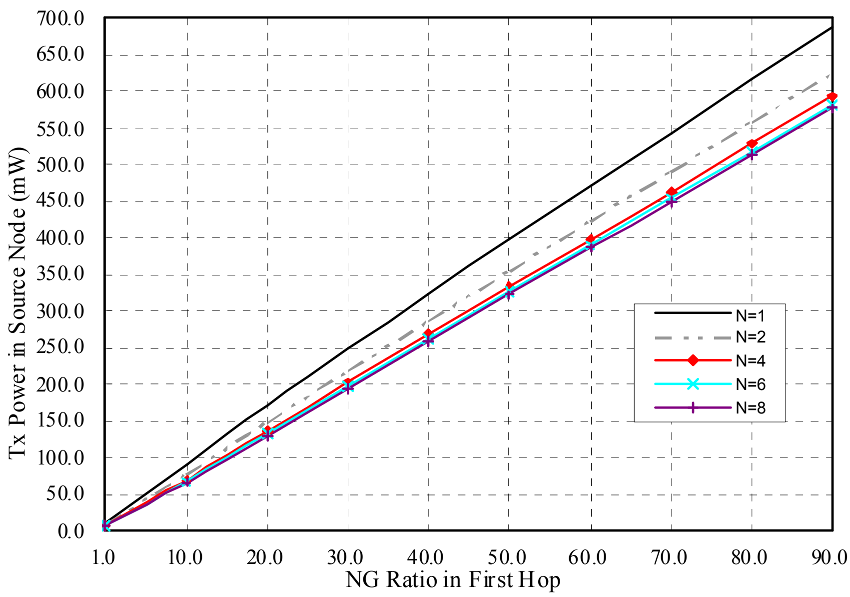


Figure 5-2: Optimal power vs. NG ratio.

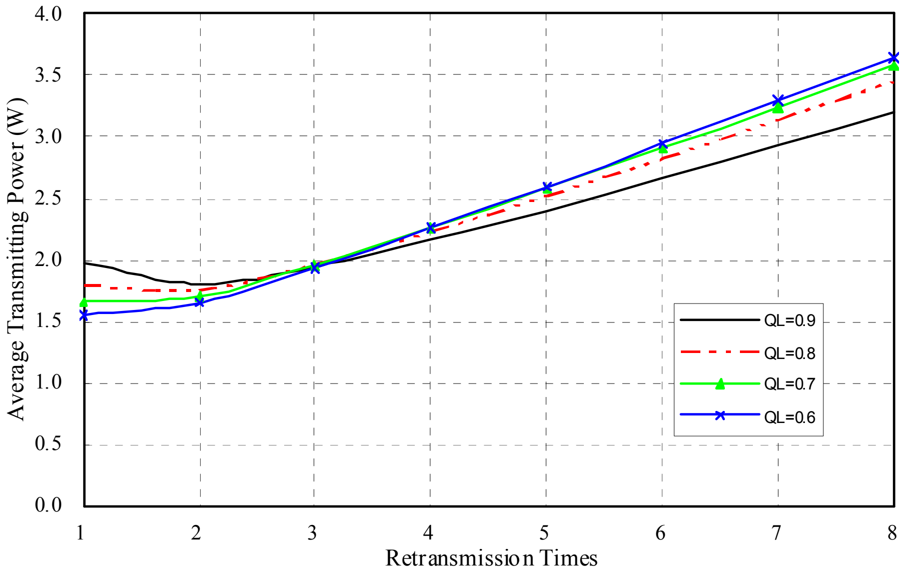


Figure 5-3: Average power consumption vs. retransmission times.

5.1.3 Numerical Results

A networking topology is shown in Figure 5-4, where three routes have been retrieved from S-node to D-node. The first route passes through S, N_1, N_2, N_3, N_4, and D with *NG* ratio of 38.2, 30.8, 22.9, 28.0, and 40.0, respectively. The second route is through S, N_5, and D with *NG* ratio of 98.2 and 83.9 while the last route through S, N_6, N_7, N_8, and D has *NG* ratio of 111.1, 125.0, 16.0, and 121.4.

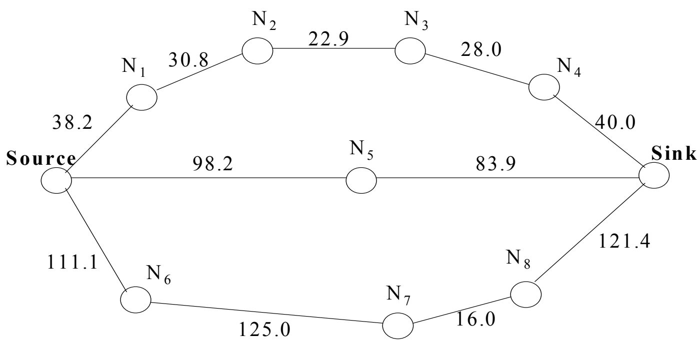


Figure 5-4: Topology used in retrieving an optimal route.

Under the constraint in Eq. (3.8), D-node can compute the optimal transmit power for every node. As a result, Table 5-2 shows the analytical and heuristic results while $N = 3$ and $QC_{e2e} = 0.8$ were given. The similar computations on $N = 1$, 2, and 4 can be done by Eq. (3.14), which can be comparable to the heuristic approach. Furthermore, the total power consumption on each of the routes is depicted in Figure 5-5. In this figure, the first path will be established for data transmission with regard to minimum power cost although the shortest-path is the second route on the topology. However, the shortest-path routing protocol, widely adopted in wired networks, may not be suitable for wireless networks. We therefore proposed a routing scheme for the power efficiency of WSNs in Chapter 3.

Table 5-2: Optimal Transmit Power at $N = 3$

Nodes in 1st route	S	N_1	N_2	N_3	N_4	***Sum***	***QC_{e2e}***
Heuristic results	0.274 mW	0.224	0.1695	0.206	0.2905	***1.164***	***0.7997***
Analytical results	0.2763 mW	0.2244	0.1693	0.2051	0.2885	***1.1636***	***0.7999***
Nodes in 2nd route	S	N_5					
Heuristic results	0.682 mW	0.5905				***1.2725***	***0.8001***
Analytical results	0.684 mW	0.5883				***1.2723***	***0.8000***
Nodes in 3rd route	S	N_6	N_7	N_8			
Heuristic results	0.7905 mW	0.8915	0.125	0.8675		***2.6745***	***0.7999***
Analytical results	0.795 mW	0.8898	0.1245	0.8655		***2.6748***	***0.8011***

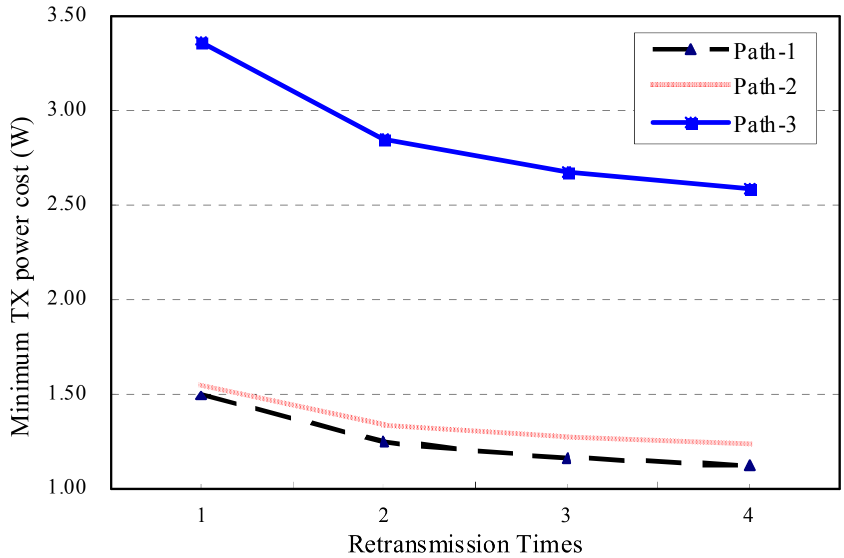


Figure 5-5: Minimum power cost for each path.

5.2 Case in Heterogeneous Networks

To study the performance of the proposed model, we create a heterogeneous network as shown in Figure 5-6. The topology consists of one wired link and nine wireless links. The number marked on each dotted line indicates the NG ratio on a wireless link. The ratio, for example, on the link between node 1 and node 2 is 30.8μW, whereas the ratio on a wired link is nearly 0. Assume that BPSK is used to modulate the waveform of transmitting frames, each of which is composed of 1024 bits. To simplify the modulation factor, we can calculate α = 1.16 while fixing β to 1 and iteratively determining the term, $\left|P_{fe} - \overline{P_{fe}}\right| < \varepsilon$. Therefore, we choose ($\alpha$, β) = (1.16, 1) and n = 1024 in the following simulations.

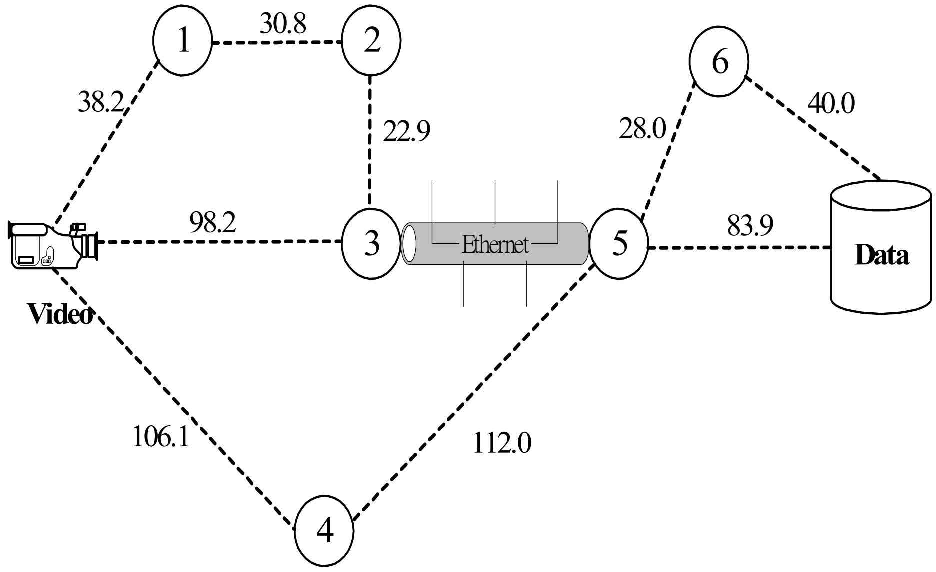


Figure 5-6: Video streaming in a heterogeneous network.

In this topology, six routes with each route containing a set of intermediate nodes from the video camera to the database are enumerated. They are, R_1 = {V, 1, 2, 3, 5, 6, D}, R_2 = {V, 3, 5, D}, R_3 = {V, 4, 5, D}, R_4 = {V, 1, 2, 3, 5, D}, R_5 = {V, 3, 5, 6, D}, and R_6 = {V, 4, 5, 6, D}. In addition, we assume each node along the route has an infinite buffer to store the forwarded frames so that no frames in a queue will be dropped. Accordingly, the individual transmit powers in any group can be determined by using our methods when the QoS constraint of an end-to-end frame-error rate is given. Under a specified QoS constraint, 50,000 video frames in our simulation were generated and sequentially delivered to the database through one of the six routes.

For performance comparison, consider a simplified minimization, i.e., Min (*Pt*), by removing the summation in Eq. (3.8). The simplification is called Method 1, and the Eq. (3.8) is called Method 2. We observe the mutual effects on end-to-end frame-error rate, ER_{e2e}, and ARQ scheme. Eight scenarios on the proposed methods are listed below.

S1: an error rate of 0.1 without ARQ (Method 1);

S2: an error rate of 0.1 without ARQ (Method 2);

S3: an error rate of 0.05 without ARQ (Method 1);

S4: an error rate of 0.05 without ARQ (Method 2);

S5: an error rate of 0.1 with ARQ (Method 1);

S6: an error rate of 0.1 with ARQ (Method 2);

S7: an error rate of 0.05 with ARQ (Method 1);

S8: an error rate of 0.05 with ARQ (Method 2).

Note that ARQ mechanism is adopted in S5-S8 cases, where an erroneous frame is retransmitted once (i.e., $N = 2$). It is not allowed to retransmit a frame more than two times. According to S1-S4 conditions, the optimal powers for each route can be individually computed by using our model. Figure 5-7 shows the average power consumes to deliver one video slice to the database on each of the six routes. The results indicate that more power is needed at an error rate of 0.05, as depicted in dotted lines, in comparison with an error rate of 0.1. Therefore, transmit power must be increased if a video stream with a higher quality is required. Interesting to notice is what percentage of video frames can successfully arrive at the database by using our power managements. The results are illustrated in Figure 5-8, which indicates that all routes in S1 and S2 have end-to-end frame error rates between 0.06 and 0.08 (or between 0.03 and 0.04 in S3 and S4). They all meet the QoS requirements since they are lower than the given constraints. Hence, the sacrifice to simplify power determination in Eq. (3.8) and Eq. (3.10) is worthy as we can observe the subtle accuracy in the resulting powers and the loss rates which are only slightly affected.

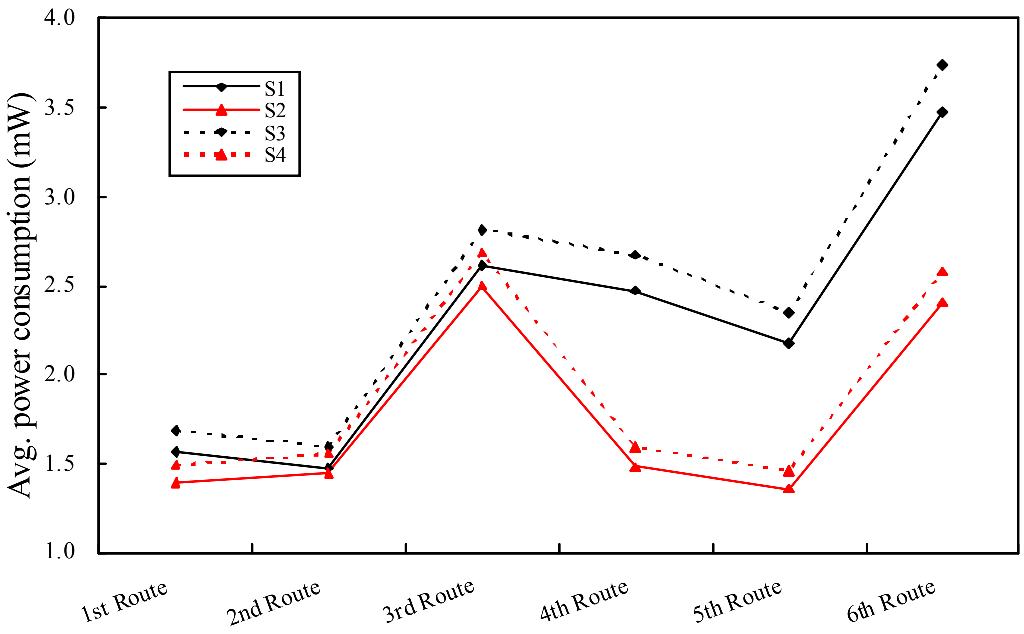


Figure 5-7: Average power consumption without using ARQ scheme.

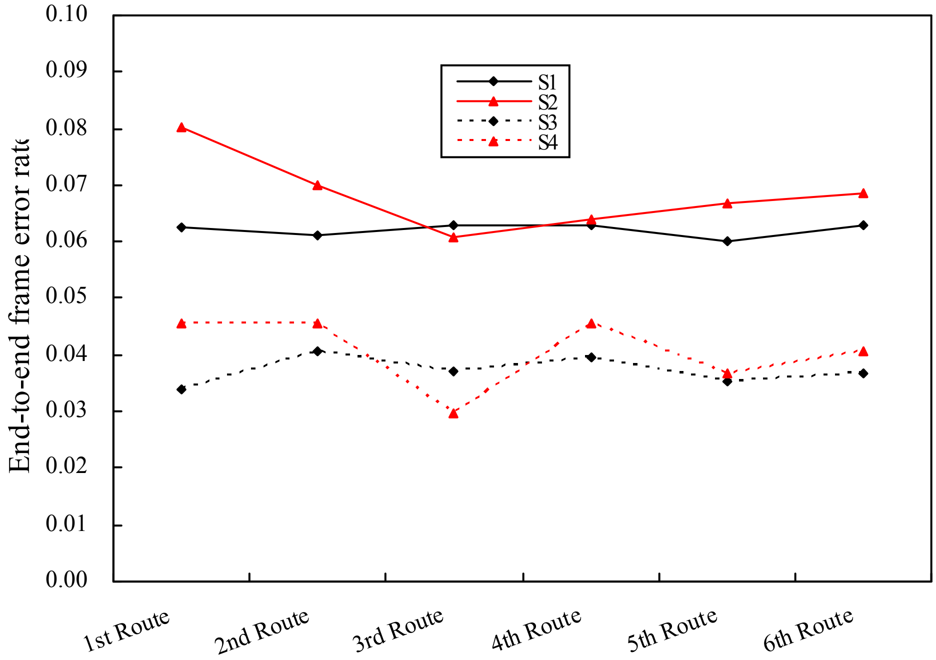


Figure 5-8: End-to-end frame error rate on each route (without ARQ).

Next, the effect of ARQ scheme was examined in our topology. When a real-time multimedia flow is generated, a wireless link is allowed to retransmit a frame once the frame is erroneous in last transmission. Using S5-S8 conditions, the similar simulations of average power consumption and end-to-end frame error rates are shown in Figure 5-9 and Figure 5-10, respectively. We can see that the average power is consumed less in Figure 5-9, as compared to that in Figure 5-7. However, the frame error rate in Figure 5-10 is much smaller than that in Figure 5-8. This demonstrates that ARQ scheme can improve the frame-error rate effectively and it consumes less power in transmitting video streams. Note that although ARQ scheme can effectively reduce the frame-error rate, it also takes additional time to process the erroneous frames.

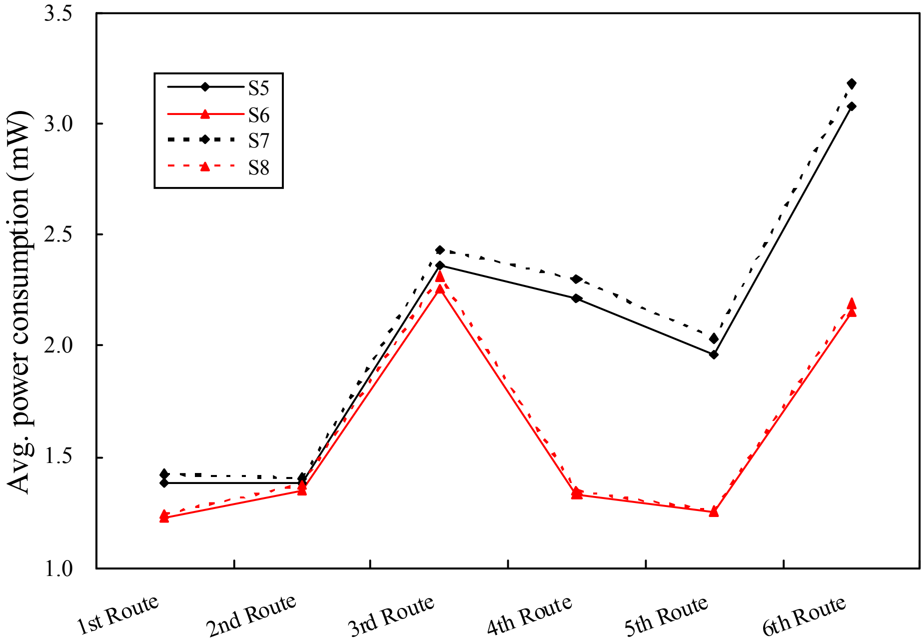


Figure 5-9: Average power consumption by using ARQ scheme.

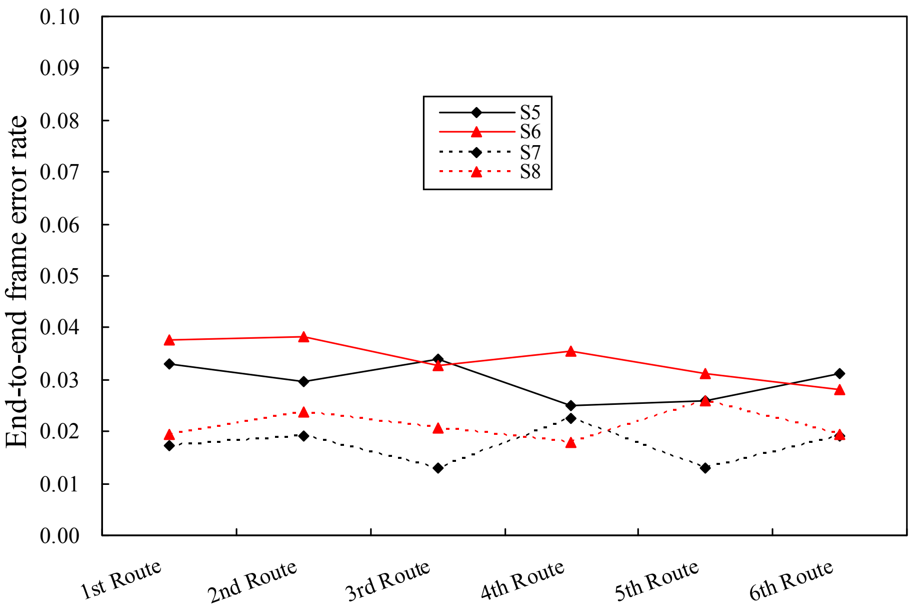


Figure 5-10: End-to-end frame error rate on each route (with ARQ).

Finally, to compare the two methods by the amount of power saving, we define the evaluation metric in Eq. (5.1).

$$\text{Save}\,(\%) = \frac{\text{Power in Method 1} - \text{Power in Method 2}}{\text{Power in Method 1}} \times 100\% \,. \tag{5.1}$$

The power saving percentage for each individual route is shown in Figure 5-11. With respect to all positive percentages, the smallest percentage is roughly 2% on the shortest route (i.e., the 2^{nd} route). This indicates that Method 2 is superior to Method 1. In other words, by using Method 2, we can more accurately calculate the individual powers because this method considers the transmission capability of each link. This also justifies why Method 2 consumes less power than Method 1.

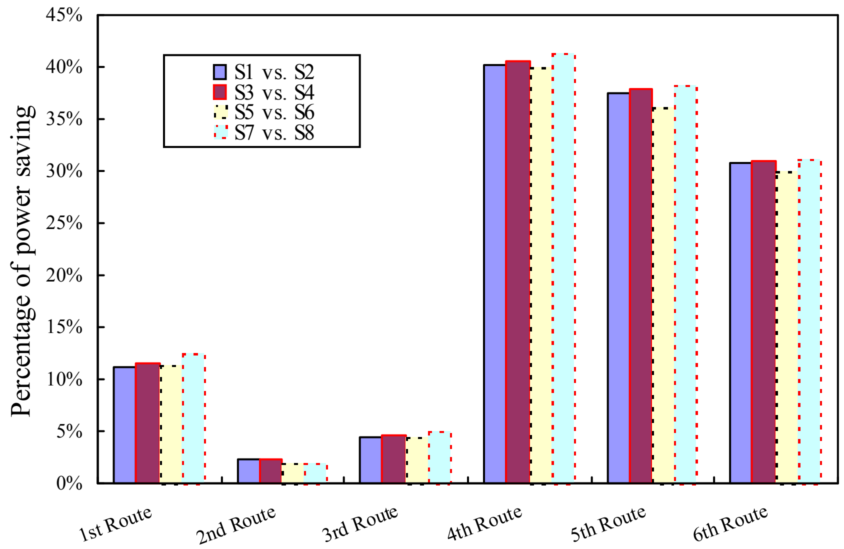


Figure 5-11: Comparison of power saving between Methods 1 and 2.

5.3 Analysis of Session Lifetime

Numerical experiments based on the algorithms proposed in Chapter 4 are performed in this section. We consider a ten-node trapezoid topology shown in Figure 5-12, where candidate routes have been discovered at a sink node. As shown in the figure, nodes were 5 meters apart from their nearest neighbors. The reserved energy at each node for a specific session was assumed to be 25 mWhr. Both shadow and fast fading were neglected in the analysis. Noise density was assumed to be -10 dBm in surrounding environment. The rest of system-related parameters were given in Table 5-3. To investigate the mutual effects on adjacent distance and reserved energy, we introduced two variables, D and Erev, where D was the distance between node 9 and node 10, and Erev was the reserved energy in node 9. The distance was assumed to vary from 6 meters to 15 meters, while Erev was varied from 25 mWhr to 75 mWhr.

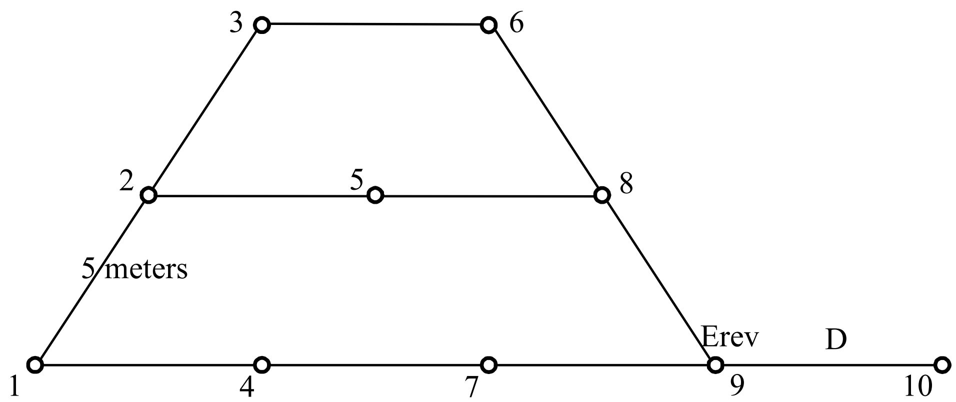


Figure 5-12: Network topology used for lifetime simulation.

Table 5-3: System-related parameters for lifetime maximization.

System-related parameters	
(α, β)	(1.05, 0.9) for GMK
N	1 (no ARQ)
n	1024 bits
m	2

We consider the multimedia session streaming from node 1 (as source) to node 10 (as sink). In this topology, three routes containing a set of intermediate nodes were enumerated: $R_1 = \{1, 4, 7, 9, 10\}$, $R_2 = \{1, 2, 5, 8, 9, 10\}$, and $R_3 = \{1, 2, 3, 6, 8, 9, 10\}$. In addition, we assumed each node along the route has an infinite buffer to store the forwarded frames, so no frames in a queue were dropped owing to buffer overflow. By the assumption, all frame errors resulted from bit interfering in wireless channels. The QoS provision to the session, *e2e* frame-error probability (ER_{e2e}), was observed at 0.005, 0.01, or 0.05 in our simulation.

Figure 5-13 shows the route lifetime of the RAPM approach when the minimum energy on each route is reserved at 25 mWhr. It is observed that the lifetime drops at exponent speed as the distance increases. For instance, on route 1, its lifetime at $ER_{e2e} = 0.05$ decays from 32 min (D = 6) to 18 min (D = 8) whereas the lifetime at $ER_{e2e} = 0.005$ just slides to 25 min (D = 6). Consequently, the adjacent distances are the most dominant factor to compute route lifetime by using our RAPM approach. In summary, network planners can adjust the locations of the nodes to achieve a longer delivery time when deploying a wireless multimedia sensor network.

In the RAPM scheme, the judgment factor *RT*, simplifying computations on route lifetime, is used to select an appropriate route from many possible routes. Hence, we examine, under the same QoS provision, the relations between the factor and the actual lifetime calculated by Eq. (4.14). The results are shown in Figure 5-14, where x-axis represents D variance and y-axis represents a ratio of judgment factor over actual route lifetime. As shown in this figure, all the ratios expose constant no matter what QoS provisions are given, and among the three routes, route 1 is selected as candidate. As a result, by using the judgment factor to select one route instead of calculating all route lifetimes, we can reduce the root computations in Eq. (4.14). Therefore, the proposed scheme is of great benefit to the wireless nodes with scarce computing resource.

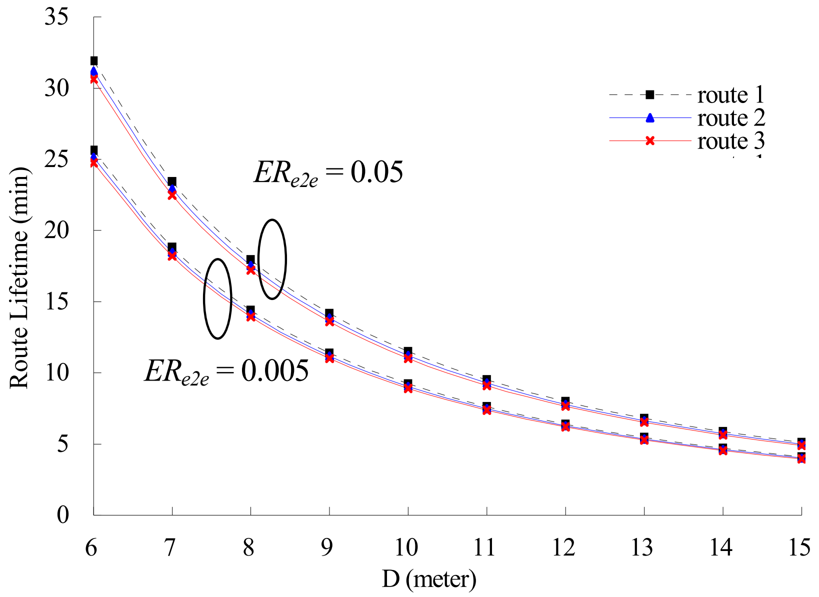


Figure 5-13: Calculation of route lifetime by adopting the RAPM approach.

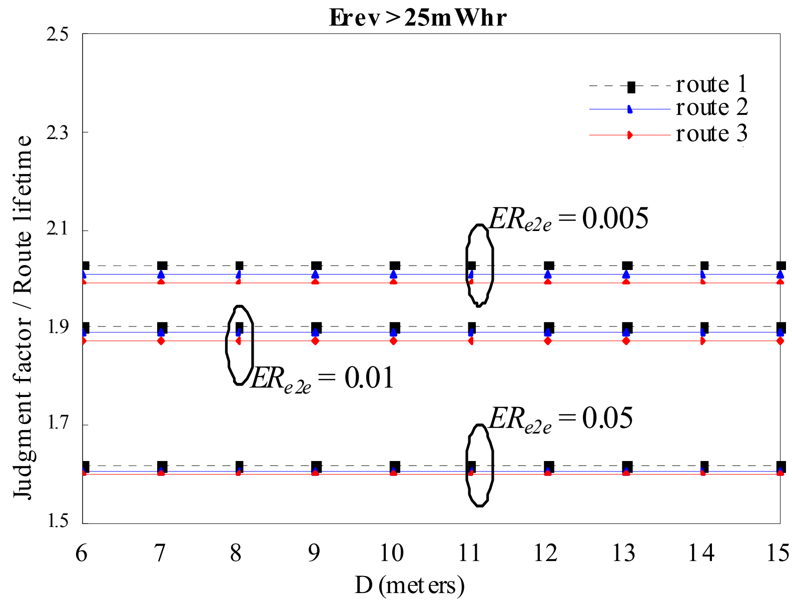


Figure 5-14: The variation of judgment factor over route lifetime.

Considering the case that several routes with the same hop counts have equal E_{min} and d_{max} in the RAPM approach, a sink node hardly discriminates which route has a longer lifetime because of obtaining identical route lifetime from Eq. (4.14). Therefore, the LAPM scheme introduced in Chapter 4 can raise the preciseness in time calculation. In addition, we proposed the RLM algorithm for the LAPM scheme to solve the MSLP, instead of using heuristic method. In order to compare this algorithm with heuristic results, we define the following evaluation metric.

$$\text{Discrepancy error} = \frac{\text{heuristic results} - \text{RLM}}{\text{heuristic results}} \times 100\% . \tag{5.2}$$

Let us set δ＝0.001 for step size and also examine both methods by three QoS provisions. As shown in Figure 5-15, the resulting errors are within 0.2%, which indicates that our algorithm is much closer to heuristic method. Depending on the time slice, the accuracy can be realistically achieved in our algorithm. However, curious to us is how many rounds are taken in converging to the optimal point. Figure 5-16 illustrates the iterations needed for route lifetime convergence when D ＝10 meters and Erev＝50 mWhr. We consider the subtraction of $\boldsymbol{t_{max}}$ from $\boldsymbol{t_{min}}$ as convergence distance, which represents in the x-axis. It is notable that the convergence distance gradually shrinks as the iterations increase. In general, the object of the process is aimed to let the convergence distance be within δ. In some cases, however, the convergence process will be terminated if the QoS constraint cannot be committed. As shown in Figure 5-16, the iterations to search a convergence point are just needed around 400 to 530 at ER_{e2e}＝0.005, whereas those are taken over 630 at ER_{e2e}=0.05. The termination is due to the situation that either of two break points in the RLM algorithm is met. Overall, in the estimation of iteration, the numbers shown in the simulation comply with Corollary 4.1.

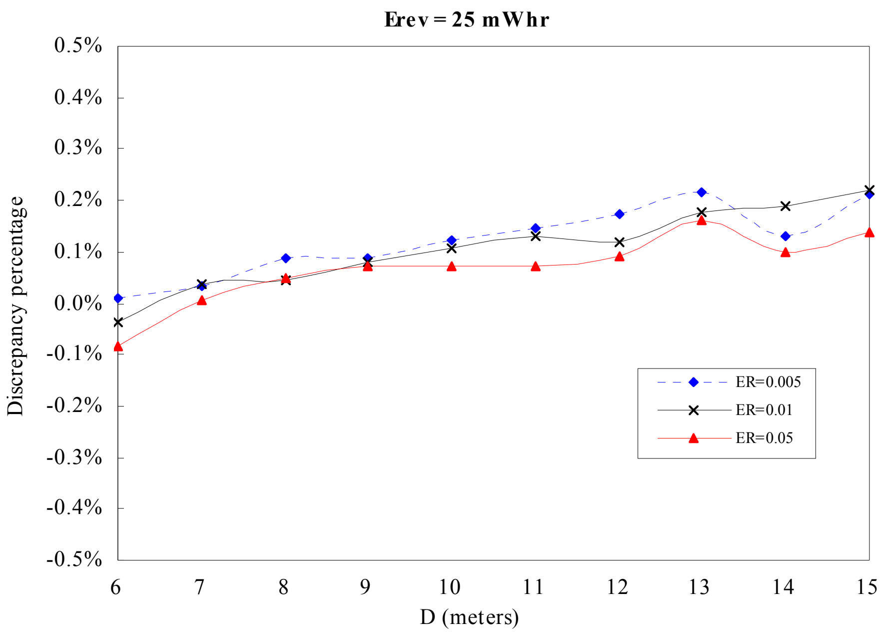


Figure 5-15: Discrepancy percentage between the RLM algorithm and heuristic determination.

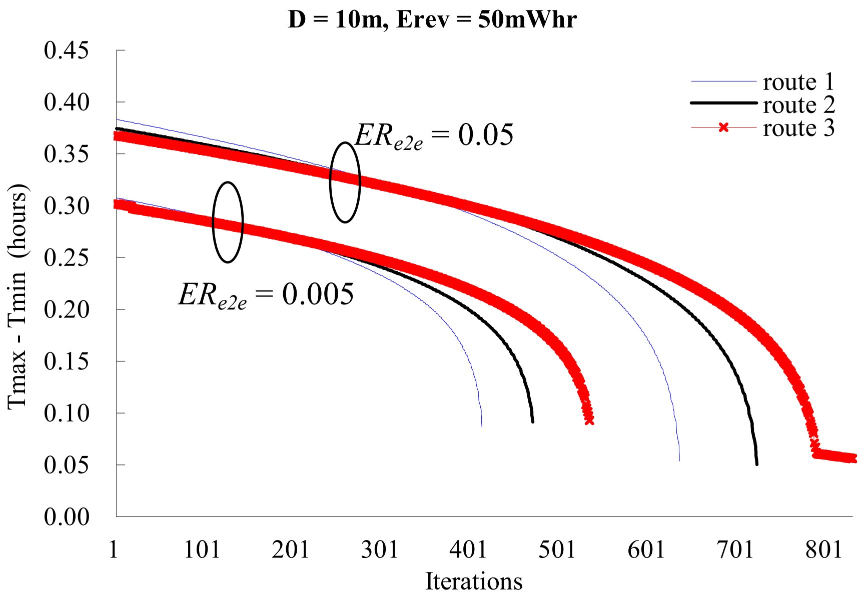
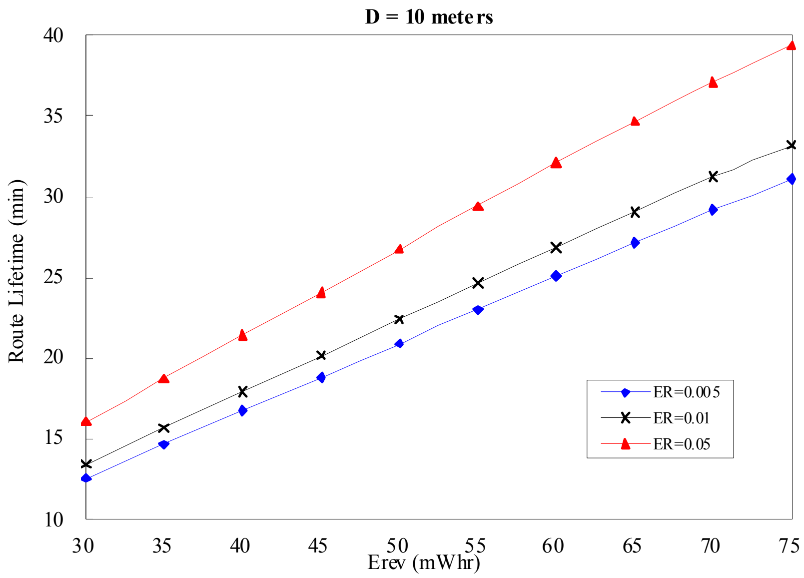


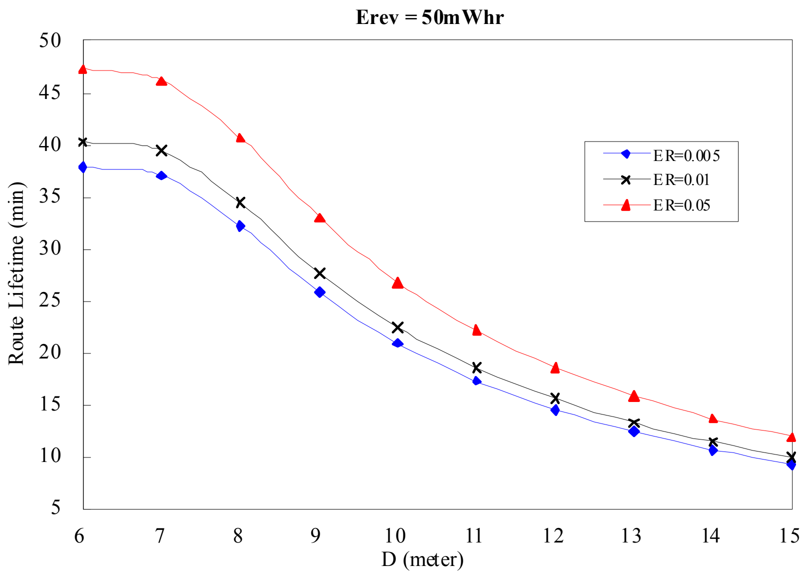
Figure 5-16: Iterations needed for lifetime convergence in the RLM algorithm.

Now let us investigate how the route lifetime would be affected by the adjacent space, the reserved energy, and the hop count. Figure 5-17 and Figure 5-18 respectively illustrate that the lifetime on route 1 varies in terms of QoS provisions and the relating factors. From Figure 5-17 (a), it is straightforward that lifetime is linearly increasing as the energy is reserved more. To the contrast, in Figure 5-17 (b), the lifetime is declining at a high speed if the distance between two nodes becomes larger. Consequently, the locations of all nodes are of significance to maintain multimedia streaming in satisfying their quality requirements, if more sessions exist in a WMSN. On the other hand, when few sessions are deployed in a system, we can make the adjacent space farther.

With respect to hop count, we assumed that the routes from node 1 to node 9 have numerous links, where adjacent distance is 5 meters and reserved energy is 25 mWhr. By performing our algorithm, the results in Figure 5-18 show that route lifetime is indistinctly decreasing with the increase of hop counts. Accordingly, the hop count of a certain route does not tremendously affect its lifetime. In summary, from Figure 5-17 and Figure 5-18, we can conclude that extending route lifetime by using the LAPM scheme primarily relies on three factors: adjacent distance, reserved energy in each node, and a given constraint (ER_{e2e}).



(a) With reserved energy.



(b) With adjacent distance.

Figure 5-17: Lifetime on route 1 determined by the RLM algorithm.

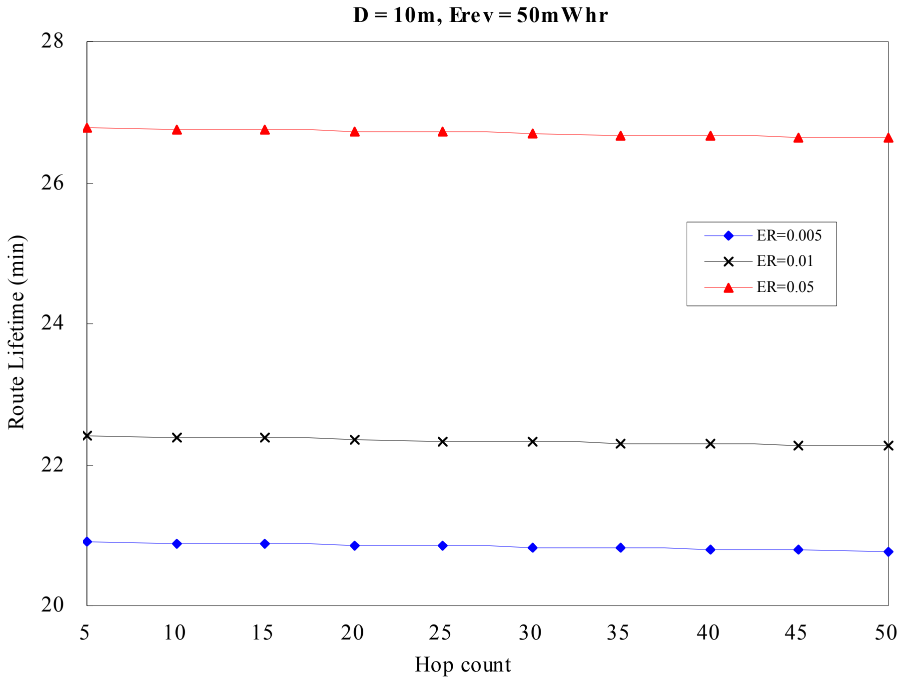


Figure 5-18: Route lifetime with respect to hop count.

Chapter 6 Conclusions and Future Works

6.1 Conclusions

In the first part of this thesis, we have presented a novel cross-layer routing scheme to select an appropriate route associated with high link quality and low power consumption. Such a route is rapidly determined by minimizing the transmit power of wireless nodes in a multi-hop sensor network. Meanwhile, under the constraint of a specified end-to-end frame error probability, the proposed scheme can establish a path where the nodes use the optimal power for packet transmission. One of the major contributions in the first part of this thesis is to derive a closed-form solution for power optimization problem. To validate the accuracy of this closed-form solution, we compare the analytical results with the simulation obtained by using a heuristic method. The comparisons have shown that the optimal transmit power determined from our analytic approach is consistent with that obtained from the heuristic method.

In the second part of this thesis, we attempt to construct a maximum session lifetime problem (MSLP) by considering end-to-end QoS constraints. The MSLP after it is converted to a max-min composite formulation is known to be NP-complete and usually solved by heuristic methods or through approximations.

Unlike the heuristic methods or through approximations, we propose two algorithms, one is referred to as route-associated power management (RAPM) algorithm and the other is referred to as link-associated power management (LAPM) algorithm, to cope with the lifetime maximization problem.

Two major contributions were made in the second part of this thesis: (1) a closed-form solution was derived to handle MSLP using the RAPM algorithm, and (2) a convergence method was devised to solve the MSLP using the LAPM algorithm. From the analytical model, we found that the RAPM scheme is suitable for the nodes that cannot afford very complicated computations. On the other hand, since an auxiliary condition is added to solve the RAPM for simplification, in terms of accuracy, the LAPM algorithm can further satisfy our needs if higher accuracy is required and computing power is sufficient in a sink node. Finally, according to the simulation, the results derived from the LAPM analytical model are very comparable to the heuristic approach.

6.2 Future Works

The proposed schemes for the lifetime maximization are mainly designed for WMSN where the nodes are assumed almost static. In the future, we will extend our research to re-routing algorithms. In addition, other significant factors, e.g., mobility and latency, will be considered in our mathematical model. Possible future works are listed below.

- When a new sensor joins a network or an existing sensor is removed from a network, we need to study how to re-route the existing path for power efficiency.
- Consider that sensor nodes may be equipped with high mobility. Therefore, network topology becomes dynamic so that re-routing calculation is needed in our system.
- Because latency is an important factor for multimedia traffic, we will analyze latency in our system model.
- Consider compression of a video stream, such as I-frame, P-frame, and B-frame. Furthermore, we determine Eq. (3.16) to obtain optimal power management associated with a QoS criterion.
- Consider all connection pairs in a system topology. Hence, the goal is to maximize system lifetime by jointly applying re-routing algorithms, adaptive power control, and different QoS criteria.

Bibliography

[1] J. Li, D. Cordes, and J. Zhang, "Power-aware Routing Protocols in Ad hoc Wireless Networks," *IEEE Wireless Commun.*, vol. 12, iss. 6, pp.69-81, Dec. 2005.

[2] M. Gerla and K. Xu, "Multimedia Streaming in Large-scale Sensor Networks with Mobile Swarms," *ACM SIGMOD Record*, vol. 32, no. 4, pp. 72-76, Dec. 2003.

[3] C.R. Lin and J. -S. Liu, "QoS Routing in Ad Hoc Wireless Networks", IEEE Journal on Selected Areas in Communications, vol. 17, no. 8, pp. 1426-38, Aug. 1999.

[4] R. Manohar and A. Scaglione, "Power Optimal Routing in Wireless Networks," *IEEE International Conference on Communications (ICC'03)*, vol. 4, pp.2979-2984, May 2003.

[5] Y. Yuan, Z. Yang, Z. He, and J. He, "An Integrated Energy Aware Wireless Transmission System for QoS Provisioning in Wireless Sensor Network," *Computer Communications*, vol. 29, iss. 2, pp. 162-172, Jan. 2006.

[6] W. Yu, Z. Sahinoglu and A. Vetro, "Energy Efficient JPEG 2000 Image Transmission over Wireless Sensor Networks," *Proc. IEEE GLOBECOM*, vol. 5, pp. 2738-43, Dec. 2004.

[7] R. Iyer and L. Kleinrock, "QoS Control for Sensor Networks", *IEEE International Conference on Communications (ICC'03)*, vol. 1, pp.517-521, May 2003.

[8] D. Kim, C.H. Min, and S. Kim, "On-demand SIR and Bandwidth-Guaranteed Routing with Transmit Power Assignment in Ad hoc Mobile Networks," *IEEE Trans. on Veh. Technology*, vol. 53, no. 4, pp. 1215-1223, Jul. 2004.

[9] A. Pandya and G. Pottie, “QoS in Ad Hoc Networks”, *IEEE 58th Vehicular Technology Conference*, vol. 5, pp. 3089-93, Oct. 2003.

[10] T.L. Sheu and Y.J. Lu, “Power Minimization with End-to-End Frame Error Constraints in Wireless Multi-hop Sensor Networks”, *International Wireless Communications and Mobile Computing Conference (IWCMC 2006)*, pp. 1045-1050, Jul. 2006.

[11] S. Guo and O. Yang, “Bandwidth Allocation in Wireless Ad-hoc Networks with Minimum-Energy Consumption”, *The 14th IEEE Proc. on Personal, Indoor and Mobile Radio Communications (PIMRC’03)*, vol. 2, pp.1059-63, Sept. 2003.

[12] C. Gao and R. Jantti, “A Reactive Power-Aware on-Demand Routing Protocol for Wireless Ad hoc Networks”, *IEEE 59th Vehicular Technology Conference*, vol. 4 pp. 2171-75, May 2004.

[13] R.L. Cruz and A.V. Santhanam, “Optimal Routing, Link Scheduling and Power Control in Multi-hop Wireless Networks,” *Proc. IEEE INFOCOM*, pp. 702-711, Apr. 2003.

[14] Y. Li and A. Ephremides, “Joint Scheduling, Power Control, and Routing Algorithm for Ad-Hoc Wireless Networks”, *Proc. of the 38th Annual Hawaii International Conference on System Sciences*, Jan. 2005.

[15] M. Chiang, “Balancing Transport and Physical Layers in Wireless Multihop Networks: Jointly Optimal Congestion Control and Power Control”, *IEEE J. on Selected Areas in Communications*, vol. 23, iss. 1, pp. 104-116, Jan. 2005.

[16] T.L. Sheu and Y.J. Lu, “"Effective Power Control for Multimedia Streaming with QoS Constraints in Heterogeneous Networks,” *IEEE Wireless Communication and*

Networking Conference, pp. 4043-4047, Mar. 2007.

[17] Y.J. Lu and T.L. Sheu, “An Efficient Routing Scheme with Optimal Power Control in Wireless Multi-hop Sensor Networks,” *Computer Communications*, vol. 30, iss. 14-15, pp. 2735-2743, Oct. 2007.

[18] P. Floreen, P. Kaski, J. Kohonen, and P. Orponen, “Lifetime Maximization for Multicasting in Energy-Constrained Wireless Networks,” *IEEE J. Select. Areas in Communications*, vol. 23, no. 1, pp. 117-126, Jan. 2005.

[19] I. Maric and R.D. Yates, “Cooperative Multicast for Maximum Network Lifetime,” *IEEE J. Select. Areas in Communications*, vol. 23, no. 1, pp. 127-135, Jan. 2005.

[20] R. Jantti and S.L. Kim, “Joint Data Rate and Power Allocation Lifetime Maximization in Interference Limited Ad hoc Networks,” *IEEE Trans. on Wireless Commun.*, vol. 5, no. 5, pp. 1086-1094, May 2006.

[21] Yi Cui, Y. Xue, and K. Nahrstedt, “A Utility-Based Distributed Maximum Lifetime Routing Algorithm for Wireless Networks,” *IEEE Trans. on Veh. Technology*, vol. 55, no. 3, pp. 797-805, May 2006.

[22] Y.T. Hou, Yi Shi, J. Pan, and S.F. Midkiff, “ Maximizing the Lifetime of Wireless Sensor Networks through Optimal Single-Session Flow Routing,” *IEEE Trans. on Mobile Computing*, vol. 5, no. 9, pp. 1255-1266, Sep. 2006.

[23] R. Madan, S. Cui, S. Lall, and A. Goldsmith, “Cross-Layer Design for Lifetime Maximization in Interference-Limited Wireless Sensor Networks,” *IEEE Trans. on Wireless Communications*, vol. 5, no. 11, pp. 3142-3152, Nov. 2006.

[24] F.P. Kelly, “Charging and Rate Control for Elastic Traffic,” *Euro. Trans. Telecomm.*, vol. 8, no. 1, pp. 33-37, Jan. 1997.

[25] C. Perkins, O. Hodson, V. Hardman, "A Survey of Packet Loss Recovery Techniques for Streaming Audio," *IEEE Network*, vol. 12, iss. 5, pp. 40-48, Sep. 1998.

[26] D. Goodman, G. Lockhart, O. Wasem, W.C. Wong, "Waveform Substitution Techniques for Recovering Missing Speech Segments in Packet Voice Communications," *IEEE Trans. on Acoustics, Speech, and Signal Processing*, vol. 34, iss. 6, pp. 1440-1448, Dec. 1986.

[27] H.P. Sze, S.C. Liew, and Y.B. Lee, "A Packet-Loss-Recovery Scheme for Continuous-Media Streaming over the Internet," *IEEE Commun. Letters*, vol. 5, iss. 3, pp. 116-118, Mar. 2001.

[28] S. Befiore, L. Crisa, M. Grangetto, E. Magli, G. Olmo, "Robust and Edge-Preserving Video Error Concealment by Coarse-to-Fine Block Replenishment," *IEEE International Conf. on ICASSP'02*, vol. 4, pp. 3281-3284, May 2002.

[29] Y.C Lee, Y. Altunbasak, and R.M. Mersereau, "Multiframe Error Concealment for MPEG-Coded Video Delivery over Error-Prone Networks," *IEEE Trans. on Image Processing*, vol. 11, iss. 11, pp. 1314-1331, Nov. 2002.

[30] M.A. Azim, M.R. Kibria, and A. Jamalipour, "An Optimized Forwarding Protocol for Lifetime Extension of Wireless Sensor Networks," in *Wireless Communications and Mobile Computing*, Feb. 2008.

[31] Xu Zhang, Qiang Gao, Jun Zhang, and Gang Wang, "Impact of Transmit Power on Throughput Performance in Wireless Ad hoc Networks with Variable Rate Control," *Computer Communications*, vol. 31, iss. 15, pp. 3638-3642, Sept. 2008.

[32] T.S. Rappaport, *Wireless Communications Principles and Practice*. Prentice Hall, 2^{nd} ed., 2002.

[33] C.-F. Wang, J.-W. Ding and C.-C. Lee, "Joint Optimization of Energy Allocation and Routing Problems in Wireless Sensor Networks," in *Wireless Communications and Mobile Computing*, 2009.

[34] W.Z. Song, W.Z. Wang, Kousha Moaveni-Nejad and X.Y. Li, "Lifetime-Maximized Cluster Association in Two-Tiered Wireless Sensor Networks," published online in *Wireless Communications and Mobile Computing*, 14 Sept. 2007.

[35] Christopher N. Ververidis and George C. Polyzos, "A Routing Layer Based Approach for Energy Efficient Service Discovery in Mobile Ad hoc Networks," in *Wireless Communications and Mobile Computing*, 2008.

[36] J. Zhang, J. Chen, and Y. Sun, "Transmission Power Adjustment of Wireless Sensor Networks Using Fuzzy Control Algorithm," in *Wireless Communications and Mobile Computing*, 2008.

[37] G. Miao, Nageen Himayat, Y. Li, and A. Swami, "Cross-Layer Optimization for Energy-Efficient Wireless Communications: A Survey," in *Wireless Communications and Mobile Computing*, 2008.

[38] J.A. Sanchez and P.M. Ruiz, "Enery-Efficient Geographic Multicast Routing for Error-Prone Wireless Sensor Networks," published online in *Wireless Communications and Mobile Computing*, 28 Aug. 2007.

[39] X. Tang and J. Xu, "Optimizing Lifetime for Continuous Data Aggregation with Precision Guarantees in Wireless Sensor Networks," *IEEE/ACM Trans. on Networking*, vol. 16, no. 4, pp. 904-917, Aug. 2008.

[40] E. Natalizio, V. Loscri, and E. Viterbo, "Optimal Placement of Wireless Nodes for Maximizing Path Lifetime," *IEEE Communications Letters*, vol. 12, no. 5, pp.

362-364, May 2008.

[41] E. Natalizio, V. Loscri, F. Guerriero and A. Violi, “Energy Spaced Placement for Bidirectional Data Flows in Wireless Sensor Network,” *IEEE Communications Letters*, vol. 13, no. 1, pp. 22-24, Jan. 2009.

[42] M. Gatzianas and L. Georgiadis, “A Distributed Algorithm for Maximum Lifetime Routing in Sensor Networks with Mobile Sink,” *IEEE Trans. on Wireless Communications*, vol. 7, no. 3, pp. 984-994, Mar. 2008.

[43] H. Wang, Y. Yang, M. Ma, J. He and X. Wang, “Network Lifetime Maximization with Cross-Layer Design in Wireless Sensor Networks,” *IEEE Trans. on Wireless Communications*, vol.7, no. 10, pp. 3759-3768, Oct. 2008.

[44] G. Deng, S.K.S. Gupta, and G. Varsamopoulos, “Maximizing Multicast Lifetime with Transmitter-Receiver Power Tradeoff in NP-Hard,” *IEEE Communications Letters*, vol. 12, no. 9, pp. 666-668, Sept. 2008.

[45] W. Wang, V. Srinivasan, and K.C. Chua, “Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays,” *IEEE/ACM Trans. on Networking*, vol. 16, no. 5, Oct. 2008.

[46] H. Hosseinmardi and F. Lahouti, “Online Multicasting Using Network Coding in Energy Constrained Wireless Ad hoc Networks,” *3rd Intl. Symposium on Wireless Pervasive Computing*, pp. 545-549, May 2008.

[47] Liu Zhixin, Guan Xinping, and Chen Cailian, “Energy-Efficient Optimal Scheme Based on Mixed Routing in Wireless Sensor Networks,” *27th Chinese Control Conference*, pp. 311-315, July 2008.

[48] L.J. Ren, Z.W. Guo, and R.Z. Ma, “Energy Assignment to Prolong the Lifetime in

Heterogeneous Wireless Sensor Network," *International Conference on Machine Learning and Cybernetics*, pp. 4057-4061, July 2008.

[49] L. Ren, Z. Guo, and R. Ma, "Prolonging Sensor Network Lifetime with Initial Energy Level Assignment," *Ninth ACIS Intl. Conf. on Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing*, pp. 231-236, Aug. 2008.

[50] M.N. Elshakankiri, M.N. Moustafa, and Y.H. Dakroury, "Energy Efficient Routing Protocol for Wireless Sensor Networks," *Intl. Conf. on Intelligent Sensors, Sensor Networks and Information Processing*, pp. 393-398, Dec. 2008.

[51] H. Zhu and G. Cao, "On Supporting Power-Efficient Streaming Applications in Wireless Environments," *IEEE Trans. on Mobile Computing*, vol. 4, no. 4, pp. 391-403, 2005.

[52] W.J. Huang, Y.W. Hong, and C.C. Jay Kuo, "Lifetime Maximization for Amplify-and-Forward Cooperative Networks," *IEEE Trans. on Wireless Communications*, vol. 7, no. 5, pp. 1800-1805, May 2008.

Vita

Yi-Jen Lu received the B.S. degree in 1994 and the M.S. degree in 1996, both from the Department of Communication Engineering, National Chiao Tung University, Hsin Chu, Taiwan. During July 1998 to 2000, he worked as a Telecom/DSP engineer in AltiGen Communications Inc., California, USA. Being a contract consultant since 2001, he has been involved in the projects of IP phone design, VoIP platform, telecom (including T1/E1, ISDN, and other trunk technologies), and voice processing (including echo cancellation, voice detection, etc.).

In 2002, he pursued a Ph.D. degree at the Dept. of Electrical Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan. His research interests include data networks, wireless networks and signal processing.

Publication List

Journal Publications

- Yi-Jen Lu and Tsang-Ling Sheu, "Lifetime Maximization Schemes under End-to-End Frame-Error Constraints in Wireless Multimedia Sensor Networks," accepted by *Wireless Communications & Mobile Computing*, Jan. 2009. (SCIE, 2007 Impact Factor = 1.225)
- Yi-Jen Lu and Tsang-Ling Sheu, "An Efficient Routing Scheme with Optimal Power Control in Wireless Multi-hop Sensor Networks," *Computer Communications*, Vol. 30, No. 14-15, pp. 2735-2743, Oct. 2007. (SCIE, 2006 Impact Factor = 0.444)

Conference Publications

- Yi-Jen Lu, Chi-Jen Huang, and Tsang-Ling Sheu, "Three-color Marking with MLCN for Cross-layer TCP Congestion Control in Multi-hop Mobile Ad Hoc Networks," *Int'l Conference on New Technologies, Mobility and Security* (NTMS), Paris, France, May 2007.

- Tsang-Ling Sheu and Yi-Jen Lu, "Effective Power Control for Multimedia Streaming with QoS Constraints in Heterogeneous Networks," *IEEE Wireless Communications and Networking Conference* (WCNC), Hong Kong, Mar. 2007.

- Tsang-Ling Sheu and Yi-Jen Lu, "Power Minimization with End-to-End Frame Error Constraints in Wireless Multi-hop Sensor Networks," *IEEE/ACM Int'l Wireless Communications and Mobile Computing* (IWCMC) Conference, Vancouver, Canada, Jul. 2006.

Books

- Yi-Jen Lu and W. H. Tsai, "TMS320C6000 DSPs: for Students and Practitioners," *Kings Information Press* (in Chinese), 2006

- Yi-Jen Lu and W. H. Tsai, "單晶片於數位信號處理的應用", *文魁出版社*, 2007