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Cross Layer Optimization for Data Gathering in Wireless Multimedia Sensor Networks within Expected Network Lifetime

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Abstract: The use of multimedia sensor nodes can significantly enhance the capability of wireless sensor networks (WSNs) for event description. In a number of scenarios, e.g., an erupting volcano, the WSNs are not deployed to work for an extremely long time. Instead, the WSNs aim to deliver continuous and reliable multimedia data as much as possible within an expected lifetime. In this paper, we focus on the efficient gathering of multimedia data in WSNs within an expected lifetime. An adaptive scheme to dynamically adjust the transmission Radius and data generation Rate Adjustment (RRA) is proposed based on a cross layer design by considering the interaction among physical, network and transport layers. We first minimize the end-to-end transmission delay in WSNs while using the minimum data generation rate. In this phase, an optimal transmission radius can be derived. Then, using this transmission radius, we adaptively adjust the data generation rate to increase the amount of gathered data. Simulation results show that the proposed RRA strategy can effectively enhance the data gathering performance in wireless multimedia sensor networks (WMSNs) by dynamically adjusting the transmission radius of sensor nodes and the data generation rate of source nodes.

Keywords: Cross layer optimization, stream data gathering, wireless multimedia sensor networks, expected network lifetime
Categories: C.2.0, C.2.1, C.2.2, C.2.3, C.2.4

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1 Introduction

Wireless Sensor Networks (WSNs) aim at collecting sensed data in a variety of applications. Simple sensor nodes, e.g., temperature and light sensors, may not be capable of describing the phenomena in WSNs. Image, audio, and video sensors can provide the information which cannot be easily described by simple sensor nodes. Using multimedia sensor nodes in WSNs can significantly enhance the capability of event description. Consequently, in wireless multimedia sensor networks (WMSNs), efficient multimedia data gathering and transmitting becomes a very important research concern [Gurse 05, Akyildiz 07, and Misra 08].

In WSNs, energy efficiency is one of the most significant research challenges since sensors are normally battery powered [Chen 09]. How to effectively use the limited power and achieve a long lifetime is considered as a critical issue. However, different scenarios, environments and applications may have different requirements. In a variety of scenarios, the WSNs are not deployed to work for an extremely long time [Shu 07c]. Instead, the sensor networks aim to deliver continuous and reliable multimedia data as much as possible within an expected lifetime without sleeping. These applications include monitoring an erupting volcano [Werner-Allen 06], rescue in a sudden earthquake, monitoring hazardous/incidental situations [Bokareva 06], etc., which actually motivates the research work in this paper.

When a WSN does not tend to work very long, the design emphasis shall be put on the full utilization of the limited energy to maximize the data gathering performance. Considering the applications above and their specific requirements, in this paper we will focus on the research problem: how to maximize the amount of the total gathered data in a base station and minimize the end-to-end transmission delay in a WMSN within an expected lifetime. Here, the expected network lifetime refers to the working time that all sensor nodes in the network are expected to achieve before any of them runs out of energy.

By virtue of theoretical analysis, we find that maximizing the total gathered data and minimizing the end-to-end delay are two contradictive requirements with respect to adjusting the transmission radius of sensor nodes. Furthermore, it is found that the transmission radius of sensor nodes and the data generation rate of source nodes are two critical factors affecting the data gathering performance. Based on this result, the above research problem is addressed by a two phase cross layer scheme, taking into account the interaction among physical layer, network layer and transport layer. We first minimize the end-to-end transmission delay in WSNs while using the minimum data generation rate. In this phase, an optimal transmission radius can be derived. Then, using this transmission radius, we adaptively adjust the data generation rate to increase the amount of gathered data. Motivated by this two phase operation, an adaptive scheme to dynamically adjust the transmission Radius and data generation Rate Adjustment (RRA) is proposed to solve the identified problem, where a Two-Phase geographical Greedy Forwarding (TPGF) algorithm [Shu 07a, Shu 08a, and Shu 09a] is applied in the network layer.

Research work in this paper contributes the following aspects: 1) To the best of our knowledge, RRA scheme is the first cross layer scheme that focuses on optimizing the multimedia streaming data gathering in WSNs within an expected network lifetime, which takes three layers into consideration; 2) The simulation results indicate that the proposed RRA strategy can effectively enhance the sensor data gathering performance by dynamically adjusting the transmission radius of sensor nodes and the data generation rate of source nodes; 3) Our RRA strategy can be used in various applications when multimedia sensor nodes are deployed in WSNs for transmitting and gathering multimedia streaming data continuously during a short period of time.

The rest of this paper is organized as follows. Section 2 presents a survey on the related work. In Section 3, we outline the network model and formulate the research problem. Section 4 discusses the cross layer design and describes the proposed RRA algorithms. In Section 5, we give a high level comparison with existing cross layer optimization schemes in WMSNs. Section 6 evaluates the performance of the RRA algorithms using simulation results. In Section 7, we conclude this paper.

2 Related Work

2.1 Related Work on Data Gathering in WSNs

In the literature, there are studies on data gathering in WSNs. These studies can be classified into three different categories: 1) maximizing lifetime of WSNs; 2) balancing data gathering in WSNs; 3) maximizing data gathering in WSNs. In this section, we review the related works in each category.

Maximizing lifetime of WSNs – The LEACH protocol proposed in [Heinzelman 00] presents a solution to data gathering problem using self-organized clusters, each of which is responsible for data collection within the cluster and data delivery to the base station. In the cluster scheme, the direct communication between sensor nodes and base station can be significantly reduced. In PEGASIS [Lindsey 00], sensor nodes are arranged into chains so that each sensor transmits and receives from a nearby neighbour node. Gathered data are transferred from node to node and eventually transmitted to the base station. In [Lindsey 01], a hierarchical scheme based on PEGASIS is proposed to reduce the consumed energy and delay during data gathering. In [Dasgupta 03], the authors consider the sensor nodes placement problem to maximize the system lifetime while each region is covered by at least one sensor node. In [Kalpakis 02], data gathering is performed in rounds in which each sensor can communicate in a single hop with the base station and all other sensors. The total number of rounds is then maximized under a given energy constraint on the sensors. In [Tan 03], PEDAP is proposed to assign weights to links and indentifies a minimum spanning tree rooted at the base station in terms of total transmission energy consumption. In [Dasgupta 03], the authors study data gathering problem in a cluster-based sensor network. During the data gathering phase, sensors perform in-network aggregation (fusion) of data packets and route to the base station while maximizing the system lifetime subject to the energy constraints. In [Hong 06], the authors focus on the data gathering problems in energy-constrained networked sensor systems. An optimal algorithm is proposed on the basis of network flows and heuristics is investigated based on self-stabilizing spanning trees and shortest paths.

Balancing data gathering in WSNs – In [Falck 04, Floréen 05], the balanced data gathering problem is formulated as a linear programming problem where a minimum achieved sensing rate is set for every individual node. This is done to balance the total amount of data received from a sensor network during its lifetime against the requirement of sufficient coverage for all the sensor locations surveyed. The authors outline an algorithm for finding the approximately optimal placements for the relay nodes, given a system of basic sensor locations and further compare its performance with a straightforward grid arrangement of the relays.

Maximizing data gathering in WSNs – In [Sadagopan 04], the data gathering problem is formulated as a linear programming problem and an approximation algorithm is proposed. This algorithm further leads to a distributed heuristic. In [Ordóñez 04], a nonlinear programming formulation is proposed to explore the trade-offs between energy consumption and the transmission rate in WSNs. In [Hong 05], the authors aim at maximizing the throughput at the base station. The issue is formulated as a constrained network flow optimization problem. A decentralized, adaptive, and modified Push-Relabel [Goldberg 86] algorithm is developed to address the optimization problem.

Although many data gathering methods for wireless sensor networks have been proposed and studied, there is no much work reported which take the expected network lifetime as the design metric. Different from existing studies, the scenarios of this study take the expected network lifetime into account. The identified research problem and the distributed cross layer scheme indicate the contributions of this paper. These aspects also distinguish our work from all the previous studies.

2.2 Related Work on Cross Layer Optimization

Some research work had been conducted on the topic of cross layer optimization in WMSNs as [Navrati 08, Tommaso 08, Shu 08d, and Shu 09c]. In [Navrati 08], the authors proposed a cross layer QoS provisioning scheme for QoS enhancement in wireless multimedia sensor networks by combining Network and MAC layers. In the network layer a statistical estimate of sensory QoS parameters is performed and a near-optimal genetic algorithmic solution is proposed to solve the NP-complete QoS-routing problem. On the other hand, the objective of the proposed MAC algorithm is to perform the QoS-based packet classification and automatic adaptation of the contention window. In [Tommaso 08], a new cross-layer communication architecture based on the time-hopping impulse radio ultra wide band technology is described, designed to reliably and flexibly *deliver QoS to heterogeneous applications in WMSNs*, by leveraging and controlling interactions among different layers of the protocol stack according to applications requirements. In [Chen 08], the authors proposed a path priority scheduling algorithm to satisfy the delay constraint of video frames while balancing energy and bandwidth usage among all the available paths. In the case that the aggregate bandwidth is still not enough to satisfy the required coding rate, the authors further exploited a cross-layer technique for adaptive coding according to path status. In [Shu 08d], the authors proposed a cross-layer approach to facilitate the continuous one shot event recording in WMSNs. The authors first proposed a maximum streaming data gathering (MSDG) algorithm and a minimum transmission delay (MTD) algorithm to adjust the transmission radius of sensor nodes in the physical layer. And then, the two-phase geographical greedy forwarding (TPGF) routing algorithm is proposed in the network layer for exploring one/multiple optimized hole-bypassing paths. In [Shu 09c], the authors proposed a context-aware cross-layer optimized Multi-Path Multi-Priority (MPMP) transmission scheme, in which the Two-Phase geographic Greedy Forwarding (TPGF) multi-path routing protocol is used in network layer to explore the maximum number of node-disjoint routing paths, and a Context-Aware Multi-path Selection algorithm (CAMS) is used in transport layer to choose the maximum number of paths from all found node-disjoint routing paths for maximizing the gathering of the most valuable information to the base station.

The key feature that distinguishes the RRA scheme from the above cross layer optimization schemes is that the RRA scheme takes three layers (physical, network and transport layers) into consideration. We further discuss and compare these cross layer optimization schemes in Section 5.

3 Network Model and Problem Formulation

3.1 Network Model

We consider a wireless sensor network consisting of N sensor nodes and a base station, which are randomly distributed over an interested region. The initial energy of each sensor node is $E_{nerSensNode}$. The total initial energy of the whole sensor network is hence given by N * $E_{nerSensNode}$. Each sensor node can dynamically adjust their transmission radius $T_{ransRadius}$. The maximum transmission radius allowed by the physical sensor node hardware is M_{axTR}. Sensor nodes have the maximum transmission capacity (bandwidth) $T_{ransCapa}$.

In addition, $S_{SourceNode}$ multimedia source nodes are deployed in the WSN with enough energy, which allows them to work continuously for several days. Alternatively, this can be considered as infinite energy in the addressed scenarios. These source nodes are different from other normal sensor nodes. All source nodes continuously generate sensed data with the minimum data generation rate R_{min} kbps, which is not larger than $T_{ransCapa}$. Each source node can dynamically change its data generation rate R. The maximum transmission capacity of each source node is $T_{ransCapaSour}$, which is larger than $T_{ransCapa}$. Each source node may use M node-disjoint routing paths for transmission multimedia streaming data. The delay constraint of multimedia streaming data is T_{Cons}.

Each node has $N_{NeighborNode}$ 1-hop neighbour sensor nodes. The location of all nodes and the base station are fixed. Sensor nodes are used as the relay nodes for transmitting the multimedia streaming data from source nodes to the base station for further processing.

Our energy model for sensors is based on the first order radio model [Shin 06], where the radio dissipates E_{elec} to power the transmitter or receiver circuitry, and E_{amp} for the transmit amplifier. The consumed energy to transmit a k-bit message over distance d is $ETx(k, d)$:

$$ETx(k, d) = E_{elec} * k + E_{amp} * k * d^2. \tag{1}$$

The consumed energy to receive this message is $ERx(k)$:

$$ERx(k) = E_{elec} * k. \tag{2}$$

Hereafter, we always use the transmission radius of a sensor node $T_{ransRadius}$ as the value of d in Eq. (1). Table 1 lists the used terms and their definitions in this paper.

Term	**Definition**
N	Number of sensor nodes
$E_{nerSensNode}$	Initial energy of each sensor node
$T_{ransRadius}$	Transmission radius of sensor nodes
M_{axTR}	Sensor hardware allowed maximum transmission radius
$T_{ransCapa}$	The maximum transmission capacity of sensor nodes
$S_{SourceNode}$	The number of multimedia source nodes
R_{min}	The minimum data generation rate of source nodes
R	The data generation rate of source nodes
$T_{ransCapaSour}$	The maximum transmission capacity of each source node
M	The number of node-disjoint routing paths of each source node
T_{Cons}	The delay constraint of multimedia streaming data
$N_{NeighborNode}$	1-hop neighbor sensor nodes
d	The transmission distance
ETx	The used energy to transmit a k-bit message over distance d
E_{elec}	The energy dissipation for the transmitter or receiver circuitry
E_{amp}	The energy dissipation for the transmit amplifier
ERx	The used energy to receive a k-bit message
$R_{ealLifeTime}$	The real lifetime of a wireless sensor network
$E_{xpeLifeTime}$	The expected lifetime of a wireless sensor network
$ECR(R_{ealSensNetwork})$	The real energy consumption rate of a sensor network
$ECR(E_{xpeSensNetwork})$	The expected energy consumption rate of a sensor network
$ECR(S_{ensNode})$	The energy consumption rate of a node within a routing path
D	The total gathered data in the base station
$D_{istance}$	The distance between a source node and the base station
D_{hop}	The average delay for transmission of each hop
$D_{otherfactors}$	The average delay contributed by all other factors
D_{e2e}	The end-to-end transmission delay
E_{xpTR}	The expected transmission radius
P_{ath}	The number of found node-disjoint routing paths
Q_{path}	The number of qualified routing path
R_{max}	The maximum data generation rate of source node

Table 1: A list of terms used in this paper and their definitions

3.2 Expected Network Lifetime

Definition 1. Node-disjoint routing path. A node-disjoint routing path is defined as a routing path which consists of a set of sensor nodes, and excluding the source node and the base station, none of these sensor nodes can be reused for forming another routing path.

Definition 2. Real lifetime of a WSN. For a given WSN, the real network lifetime $R_{ealLifeTime}$ is defined as the working time until any sensor node runs out of energy.

Definition 3. Expected lifetime of a WSN. For a given WSN, the expected lifetime $E_{xpeLifeTime}$ is defined as the working time that all sensor nodes are expected to achieve before any of them runs out of energy.

Definition 2 reflects the lower bound of the real lifetime of a WSN. We adopt this lower bound in this paper because the failure of any node may still cause serious problems, e.g., the only transmission path may be disconnected, even if WSNs are generally fault-tolerant.

Theorem 1. For a given sensor network, to guarantee the expected network lifetime $E_{xpeLifeTime}$, the data generation rate R and transmission radius $T_{ransRadius}$ should satisfy:

$$(R / M) * (2 * E_{elec} + E_{amp} * T_{ransRadius}^{2}) \leq E_{nerSensNode} / E_{xpeLifeTime}. \tag{3}$$

Proof: To determine the lifetime of a WSN, we need to develop the energy consumption. According to Definition 2, the real energy consumption rate of a sensor network $ECR(R_{ealSensNetwork})$ is given by

$$ECR(R_{ealSensNetwork}) = N * E_{nerSensNode} / R_{ealLifeTime}. \tag{4}$$

According to Definition 3, the expected energy consumption rate $ECR(E_{xpeSensNetwork})$ of a sensor network is expressed as

$$ECR(E_{xpeSensNetwork}) = N * E_{nerSensNode} / E_{xpeLifeTime}. \tag{5}$$

In order to guarantee the expected lifetime of a sensor network, the real lifetime of a sensor network must be not smaller than the expected lifetime. This indicates that the real energy consumption rate must not be larger than the expected energy consumption rate:

$$ECR(R_{ealSensNetwork}) \leq ECR(E_{xpeSensNetwork}). \tag{6}$$

Substituting Eq. (4) (5) into the equation above, we have

$$E_{nerSensNode} / R_{ealLifeTime} \leq E_{nerSensNode} / E_{xpeLifeTime}. \tag{7}$$

This expression shows that the energy consumption rate of any sensor node should not be larger than 1/N expected energy consumption rate of the whole sensor network. For the end-to-end node-disjoint streaming data transmission, any sensor node within a transmission path has the energy consumption rate $ECR(S_{ensNode})$ when the source node equally uses M node-disjoint routing paths for transmission multimedia streaming data:

$$ECR(S_{ensNode}) = E_{nerSensNode} / R_{ealLifeTime} \tag{8}$$

and

$$ECR(S_{ensNode}) = (R / M) * (2 * E_{elec} + E_{amp} * T_{ransRadius}{}^{2}). \tag{9}$$

According to Eq. (7), (8), and (9), we have

$$(R / M) * (2 * E_{elec} + E_{amp} * T_{ransRadius}{}^{2}) \leq E_{nerSensNode} / E_{xpeLifeTime}. \tag{10}$$

As a consequence, to guarantee the expected lifetime, we must find an appropriate data generation rate R and a transmission radius $T_{ransRadius}$ to satisfy Eq. (3).

3.3 Problem Formulation

In this paper, we investigate efficient data gathering in WMSNs. In particular, the research problem is formulated as: **how to maximize the total amount of gathered data in the base station and minimize the end-to-end transmission delay in the WMSN within an expected lifetime.** Naturally, there are two optimization goals: 1) maximizing the total gathered data in the base station; 2) minimizing the end-to-end transmission delay in the WMSN. Here, we define the total gathered data in the base station and the end-to-end transmission delay as follows:

Definition 4. Total gathered data. Within an expected network lifetime $E_{xpeLifeTime}$, a base station can receive the total amount of data D from $S_{SourceNode}$ source nodes

$$D = S_{SourceNode} * R * E_{xpeLifeTime}, (R_{min} \leq R \leq T_{ransCapaSour}). \tag{11}$$

Definition 5. End-to-end transmission delay. Given a distance $D_{istance}$ between a source node $S_{SourceNode}(i)$ and the base station, when using any greedy forwarding routing protocol, with the average delay of each hop $D_{hop} + D_{otherfactors}$, the end-to-end transmission delay D_{e2e} can be defined as

$$D_{e2e} = \lceil D_{istance} / T_{ransRadius} \rceil * (D_{hop} + D_{otherfactors}), \tag{12}$$

where D_{hop} is the delay for transmission and $D_{otherfactors}$ stands for the delay contributed by all other factors, such as MAC layer delay and queuing delay. In this paper, for the sake of simplicity, we consider the average delay of each hop D_{hop} + $D_{otherfactors}$ as a fixed value [Chang 07].

Theorem 2. Goal 1) maximizing the total gathered data in the base station and Goal 2) minimizing the end-to-end transmission delay in the sensor network are two contradictive requirements with respect to the transmission radius $T_{ransRadius}$.

Proof: According to Definition 4 and Theorem 1, the first goal can be formulated as ***Problem Formulation 1)***:

$$\text{Maximize} \quad D = S_{SourceNode} * R * E_{xpeLifeTime} \tag{13}$$

Subject to:

$$R_{min} \leq R \leq T_{ransCapaSour} \tag{14}$$

$$T_{ransRadius} \leq M_{axTR} \tag{15}$$

$$(R / M) * (2 * E_{elec} + E_{amp} * T_{ransRadius}^{\ 2}) \leq E_{nerSensNode} / E_{xpeLifeTime} \tag{16}$$

Since both $S_{SourceNode}$ and $E_{xpeLifeTime}$ are fixed parameters in Eq. (13), maximizing the total gathered data D is equivalent to maximizing R. Moreover, Eq. (16) shows that the higher R can be achieved with the smaller $T_{ransRadius}$.
According to Definition 5 and Theorem 1, the second goal can be formulated as ***Problem Formulation 2)***:

$$\text{Minimize} \ D_{e2e} = \lceil D_{istance} / T_{ransRadius} \rceil * (D_{hop} + D_{otherfactors}) \tag{17}$$

Subject to:

$$T_{ransRadius} \leq M_{axTR} \tag{18}$$

$$R_{min} \leq R \leq T_{ransCapaSour} \tag{19}$$

$$(R / M) * (2 * E_{elec} + E_{amp} * T_{ransRadius}^{\ 2}) \leq E_{nerSensNode} / E_{xpeLifeTime} \tag{20}$$

Since $D_{istance}$, D_{hop} and $D_{otherfactors}$ are fixed parameters in Eq. (17), minimizing D_{e2e} is equivalent to maximizing $T_{ransRadius}$. As a consequence, with respect to the transmission radius $T_{ransRadius}$, the two optimal goals are two contradictive requirements.

On the basis of Theorem 2, the research problem can be solved in a two phase strategy. We first minimize the end-to-end transmission delay in WSNs while using the minimum data generation rate. In this phase, an optimal transmission radius can be derived. Then, using this transmission radius, we adaptively adjust the data generation rate to increase the amount of gathered data. This strategy is a cross layer design solution, considering the interaction among physical, network and transport layers.

4 Cross Layer Design and RRA Scheme

The cross layer framework of RRA scheme is shown in Fig.1. The cross layer interaction in RRA scheme includes four steps: 1) choose the optimal transmission radius of sensor nodes in physical layer; 2) discover multiple routing paths by using TPGF in network layer; 3) select the qualified multiple paths in transport layer; 4) adjust the data generation rate of source nodes in physical layer.

4.1 Adjustment on Transmission Radius of Sensor Nodes in Physical Layer

In physical layer of sensor nodes, we mainly consider how to dynamically adjust the transmission radius of sensor nodes, which is identified as one of the major factors in Theorem 1. In this Subsection, we minimize the end-to-end transmission delay in the

WSN while using the minimum data generation rate R_{min} within an expected network lifetime. Comparing with the *problem formulation 2)* in Theorem 2, the expected network lifetime serves as an extra constraint.

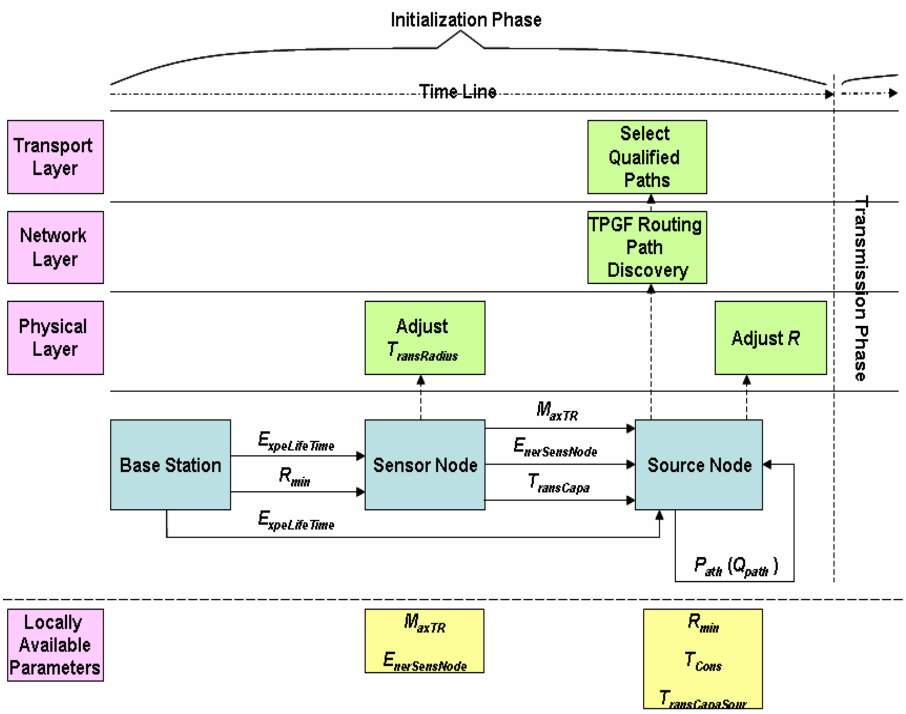

Figure 1: The cross layer framework of RRA scheme

Theorem 3. Given a sensor network with an expected network lifetime $E_{xpeLifeTime}$, when the minimum data generation rate R_{min} is used, to guarantee the expected network lifetime, the upper bound of the transmission radius $T_{ransRadius}$ is:

$$Min(((E_{nerSensNode} / (E_{xpeLifeTime} * R_{min}) - 2 * E_{elec}) / E_{amp})^{1/2},\ M_{axTR}),(R_{min} \le T_{ransCapa}) \tag{21}$$

where *Min(para1, para2)* is the function which returns the smaller value.

Proof: According to Theorem 1, when the minimum data generation rate R_{min} is used and the sensor network consumes the energy with the expected energy consumption rate $ECR(E_{xpeSensNetwork})$, we can calculate the expected transmission radius E_{xpTR} as:

$$E_{xpTR} = ((E_{nerSensNode} / (E_{xpeLifeTime} * R_{min}) - 2 * E_{elec}) / E_{amp})^{1/2}. \tag{22}$$

Thus, when E_{xpTR} is used to transmit streaming data, the energy consumption rate of sensor nodes is given by

$$ECR(E_{xpTR}) = R_{min} * (2 * E_{elec} + E_{amp} * E_{xpTR}{}^{2}). \quad (23)$$

On the other hand, sensor nodes are physically allowed to use maximum transmission radius M_{axTR} to transmit data. Hence, when M_{axTR} is used to transmit data, the energy consumption rate $ECR(M_{axTR})$ of sensor nodes is given by

$$ECR(M_{axTR}) = R_{min} * (2 * E_{elec} + E_{amp} * M_{axTR}{}^{2}). \quad (24)$$

To guarantee the expected network lifetime:

- If $ECR(E_{xpTR}) \leq ECR(M_{axTR})$, then we can only choose E_{xpTR} for streaming data transmission. If we consume energy with a larger energy consumption rate than $ECR(E_{xpTR})$, the expected network lifetime cannot be guaranteed.
- If $ECR(M_{axTR}) < ECR(E_{xpTR})$, then we can only choose M_{axTR} for streaming data transmission. If the M_{axTR} is the physically allowed maximum transmission radius, it is impossible to have a longer transmission radius beyond the hardware constraint.

As a result, to guarantee the expected network lifetime, the upper bound of the transmission radius $T_{ransRadius}$ is given in (21).

According to Theorem 3, the problem of minimizing the end-to-end transmission delay in sensor network while using the minimum data generation rate R_{min} within an expected network lifetime can be converted from the *Problem Formulation 2)* and formulated as:

$$\text{Minimize} \quad D_{e2e} = \lceil D_{istance} / T_{ransRadius} \rceil * (D_{hop} + D_{otherfactors}) \quad (25)$$

Subject to:

$$T_{ransRadius} \leq Min(((E_{nerSensNode} / (E_{xpeLifeTime} * R_{min}) - 2 * E_{elec}) / E_{amp})^{1/2}, M_{axTR}) \quad (26)$$

Based on Eq. (25), when the upper bound of $T_{ransRadius}$ is used, the end-to-end transmission delay can be minimized.

4.2 Multipath Routing in Network Layer

In WSNs, using multiple paths routing can increase transmission performance. In network layer, a key issue is: **how to find multiple optimized routing paths in terms of distance and end-to-end delay minimization with energy constraint**.

In [Shu 07a, Shu 08a, and Shu 09a], we proposed a new multipath routing protocol TPGF, which is one of the first routing protocols designed for WMSNs. It allows any source node to explore the maximum number of approximately optimal node-disjoint routing paths in network layer with the aim to minimize the path length and the end-to-end transmission delay under the energy consumption constraint. TPGF includes two phases. In the first *geographic forwarding* phase, TPGF provides a new method to bypass holes other than using the face routing. It guarantees to find the deliverable routing path. The second *path optimization* phase in TPGF provides *label based optimization* method to optimize the routing path found by using the

TPGF with the minimum number of nodes. TPGF finds one path per execution and can be executed repeatedly to find more node-disjoint routing paths. It successfully addressed four important issues: 1) Hole-bypassing; 2) Guarantee path exploration result; 3) Routing path optimization; and 4) Node-disjoint multipath transmission. Fig.2 shows an example of TPGF multipath routing which is implemented in a new sensor network simulator NetTopo [Shu 07b, Shu 08b, Shu 08c, and Shu 09b]. In Fig.2, eight routing paths are found from the source node (red colour) to the base station (green colour).

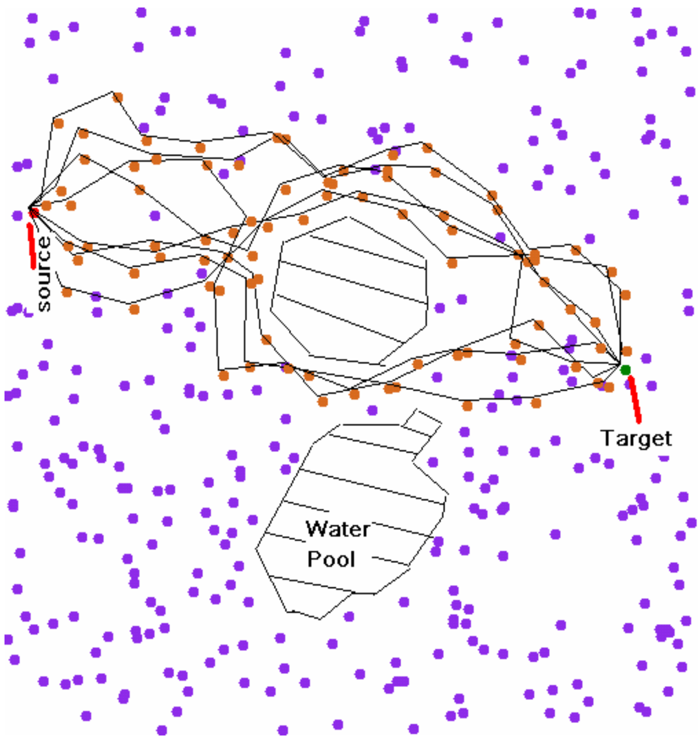

Figure 2: An example of TPGF: Eight paths are found

After adjusting the transmission radius in sensor nodes, each source node tries to use TPGF to explore as many routing paths as possible. The number of exploration times and the number of found routing paths in TPGF is bounded by two variables as presented in the following Theorem 4 and Theorem 5. It is noteworthy that these two theorems are new contributions in this paper and absent in [Shu 07a, Shu 08a].

Theorem 4. For any given source node $S_{SourceNode}(i)$ with $N_{NeighborNode}$ number of 1-hop neighbour nodes within its transmission radius, it can have maximum $N_{NeighborNode}$ number of possible node-disjoint routing paths for transmitting data.

Theorem 5. For any given source node $S_{SourceNode}(i)$, the maximum number of possible node-disjoint routing paths is affected by routing algorithms.

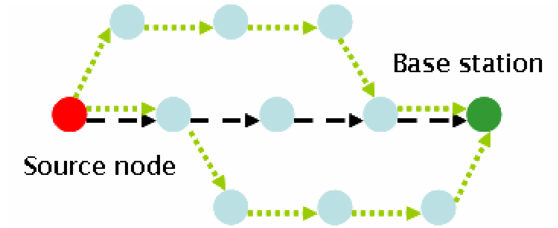

Figure 3: Multipath GPSR vs. LMR

Proof: For instance in Fig.3, if using the greedy forwarding routing algorithm (GPSR [Karp 00]), the number of routing paths can be only one (dashed path) with a short end-to-end transmission delay. However, if using the label-based multipath routing (LMR) [Hou 04], the number of routing paths can be two (dotted path) with a relative longer end-to-end transmission delay.

Theorem 5 demonstrates a confliction between two different design principles: 1) always explore the shortest routing path in each round; 2) explore more redundant routing paths while scarifying the end to end transmission delay. It is noteworthy that TPGF uses "always explore the shortest transmission path in each round" as the criteria. The primary motivation is that the shortest transmission path generally has the smallest end-to-end delay which may satisfy the delay constraint of multimedia streaming data.

4.3 Multipath Selection in Transport Layer

It is clear that the found routing paths in Fig.2 have different number of hops. Hence, not all of them can be used for transmitting multimedia streaming data since a long routing path with a long end-to-end transmission delay may not satisfy the delay constraint of multimedia streaming data.

In transport layer, a key research issue is: **how to choose the maximum number of paths from all found node-disjoint routing paths to maximize multimedia data transmission within the end-to-end delay requirement**. After exploring the routing paths, each source node tries to select as many qualified routing as possible. It is clear that the maximum number of chosen paths is bounded by the found node-disjoint routing paths P_{ath}.

Definition 6. Qualified routing path. For a given source node, which has a routing path found by TPGF, if the end-to-end delay of this routing path is not larger than the delay constraint of multimedia streaming data T_{Cons}, we consider this path as a qualified routing path.

According to Definition 6, the number of qualified routing path Q_{path} is bounded by P_{ath}: $Q_{path} \le P_{ath}$. The delay constraint of multimedia data will reduce the number of useable routing paths.

4.4 Adjustment on Data Generation Rate of Source Nodes in Physical Layer

In this Subsection, we increase the data generation rate R while using the derived transmission radius $T_{ransRadius}$ in Section 4.1. According to Theorem 3, the transmission radius can be either E_{xpTR} or M_{axTR} when the expected network lifetime varies. We discuss two situations.

Theorem 6. When sensor nodes use E_{xpTR} for streaming data transmission with the minimum data generation rate R_{min}, the source nodes can not increase the data generation rate R.

Proof: The E_{xpTR} is given in Eq. (22) when the minimum data generation rate R_{min} is used. If sensor nodes use E_{xpTR} and still increase the data generation rate R, then the expected network lifetime cannot be guaranteed.

Theorem 7. When sensor nodes use M_{axTR} for streaming data transmission with the minimum data generation rate R_{min}, the source nodes can increase the data generation rate R and the maximum data generation rate R_{max} is expressed as

$$R_{max} = Min(Q_{path} * (Min(E_{nerSensNode} / (E_{xpeLifeTime} * (2 * E_{elec} + E_{amp} * M_{axTR}{}^{2})), T_{ransCapa})), T_{ransCapaSour}). \tag{27}$$

where $Min(para1, para2)$ is the function which returns the smaller value.

Proof: M_{axTR} is the physically allowed maximum transmission radius which is constrained by the sensor node hardware capacity. When M_{axTR} is used with the minimum data generation rate R_{min}, the $ECR(M_{axTR})$ is smaller than $ECR(E_{xpTR})$ according to Theorem 3. Thereafter, we can increase the data generation rate R to the maximum data generation rate R_{max} until the new $ECR(M_{axTR})$ is equal to $ECR(E_{xpTR})$ as shown below

$$ECR(M_{axTR}) = ECR(E_{xpTR}) \tag{28}$$

$$(R_{max} / Q_{path}) * (2 * E_{elec} + E_{amp} * M_{axTR}{}^{2}) = R_{min} * (2 * E_{elec} + E_{amp} * E_{xpTR}{}^{2}). \tag{29}$$

Referring to Eq. (22), we obtain

$$R_{max} = Q_{path} * (E_{nerSensNode} / (E_{xpeLifeTime} * (2 * E_{elec} + E_{amp} * M_{axTR}{}^{2})). \tag{30}$$

Because each routing path has the maximum transmission capacity $T_{ransCapa}$, the R_{max} should be constrained and can be shown as

$$R_{max} = Q_{path} * (Min(E_{nerSensNode} / (E_{xpeLifeTime} * (2 * E_{elec} + E_{amp} * M_{axTR}{}^{2})), T_{ransCapa})). \tag{31}$$

Furthermore, the maximum data generation rate R_{max} is bounded by the maximum transmission capacity (bandwidth) of source nodes $T_{ransCapaSour}$: $R_{max} \leq T_{ransCapaSour}$, thus, we have

$$R_{max} = Min(Q_{path} * (Min(E_{nerSensNode} / (E_{xpeLifeTime} * (2 * E_{elec} + E_{amp} * M_{axTR}{}^{2})), T_{ransCapa})), T_{ransCapaSour}). \quad (32)$$

Theorem 7 is proved.

4.5 Transmission Radius and Data Generation Rate Adjustment Algorithms

In this section, we come back to the main research problem in this paper, which is defined in Subsection 3.3. Two distributed transmission Radius and data generation Rate Adjustment (RRA) algorithms are proposed to address the issue via a cross layer design. These algorithms are based on the assumption that every sensor node can dynamically adjust its transmission radius and every source node can dynamically adjust its data generation rate.

RRA ALGORITHM ON SENSOR NODES

Input:

1) $E_{xpeLifeTime}$, 2) $E_{nerSensNode}$, 3) M_{axTR}, 4) R_{min}

Output:

M_{axTR} *or* E_{xpTR}

Algorithm:

Initialize $E_{xpeLifeTime}$, $E_{nerSensNode}$, M_{axTR}, R_{min}
    E_{xpTR} = Get_E_{xpTR}($E_{xpeLifeTime}$, $E_{nerSensNode}$, R_{min}) // Eq. (22)
    If $E_{xpTR} \le M_{axTR}$ Then
        $T_{ransRadius} = E_{xpTR}$
    Else
        $T_{ransRadius} = M_{axTR}$
    End If
        Return $T_{ransRadius}$
End If

Figure 4: Pseudo code of the RRA algorithm on sensor nodes

When applying RRA algorithms to source nodes and other normal sensor nodes, the input parameters are different. When applying RRA algorithm for sensor nodes, four inputs are needed: 1) $E_{xpeLifeTime}$, 2) $E_{nerSensNode}$, 3) M_{axTR}, and 4) R_{min}. The output is M_{axTR} or E_{xpTR}. When applying RRA algorithm for source nodes, eight inputs are needed: 1) $E_{xpeLifeTime}$, 2) $E_{nerSensNode}$, 3) M_{axTR}, 4) R_{min}, 5) P_{ath}, 6) $T_{ransCapa}$, 7) T_{Cons}, and 8) $T_{ransCapaSour}$. The output is: R_{max} or R_{min}.

In Fig.1, during the initialization phase, the base station will flood the $E_{xpeLifeTime}$, R_{min} in the WSN, so that these two inputs can be obtained by all nodes. For source nodes, the node-disjoint routing paths P_{ath} (network layer) and Q_{path} (transport layer) can be found by using TPGF with the output $T_{ransRadius}$ of sensor nodes, and $E_{nerSensNode}$, M_{axTR} and $T_{ransCapa}$ can be obtained from the neighbour sensor nodes.

RRA ALGORITHM ON SOURCE NODES

Input:

1) $E_{xpeLifeTime}$, 2) $E_{nerSensNode}$, 3) M_{axTR}, 4) R_{min}, 5) P_{ath}, 6) $T_{ransCapa}$, 7) T_{Cons}, 8) $\mathrm{T}_{ransCapaSour}$

Output:

R_{max} *or* R_{min}

Algorithm:

Initialize $\mathrm{E_{xpeLifeTime}, E_{nerSensNode}, M_{axTR}, R_{min}, P_{ath}, T_{ransCapa}, T_{Cons},}$
        $\mathrm{T_{ransCapaSour}}$
If $\mathrm{P_{ath}} > 0$ Then
    $\mathrm{Q_{path}}$ = Return_Qualified_Path($\mathrm{P_{ath}, T_{Cons}}$) // Definition 6
    $\mathrm{E_{xpTR}}$ = Get_$\mathrm{E_{xpTR}}$($\mathrm{E_{xpeLifeTime}, E_{nerSensNode}, R_{min}}$) // Eq. (22)
    If $\mathrm{E_{xpTR} \leq M_{axTR}}$ Then
        $\mathrm{R = R_{min}}$
    Else // $\mathrm{M_{axTR} < E_{xpTR}}$
        $\mathrm{R_{max}}$ = Get_$\mathrm{R_{max}}$($\mathrm{E_{xpeLifeTime}, E_{nerSensNode}, M_{axTR}, T_{ransCapa}, T_{ransCapaSour}, Q_{path}}$)
        $\mathrm{R = R_{max}}$
    End If
        Return R
End If

Figure 5: Pseudo code of the RRA algorithm on source nodes

Without loss of generality, we simplified the end-to-end delay such that only the number of hops and the average delay per hop are considered while other factors, e.g. MAC layer delay and queuing delay, are not accounted for the transmission delay. In such case, the impacts of the transmission radius $T_{ransRadius}$ and the data generation rate R are emphasized.

Figs.4 and 5 present the algorithm of the proposed RRA scheme on sensor nodes and source nodes respectively.

5 High Level Comparison with Other Existing Schemes

In this section, in order to highlight the novelty and the key different feature of RRA scheme, we provide a high level comparison with other existing cross layer optimization scheme in wireless multimedia sensor networks.

- Cross Layer QoS Provisioning Scheme [Navrati 08]
  - Considered layer: MAC layer and network layer.
  - Optimization goal: Obtain optimal QoS-routes with application specific QoS requirements.
  - Designed new routing algorithm in network layer: No.
  - Considered Energy Efficiency: Yes, but the method for achieving the energy efficiency was not clear described in the paper.

  - Unique feature: QoS-aware, if the QoS routing algorithm is successful in providing a set of near-optimal QoS routes, then the QoS-based MAC scheme efficiently share sensory channel resources.
- Cross Layer Quality of Service Support [Tommaso 08]
  - Considered layer: Physical layer, MAC layer and network layer.
  - Optimization goal: Provide QoS in wireless multimedia sensor networks based on time hopping impulse radio UWB communications.
  - Designed new routing algorithm in network layer: No.
  - Considered Energy Efficiency: No.
  - Unique feature: Cross layer module coordinates to share the transmission medium among devices, schedules transmissions of data packets and assigns data rates to different flows based on application requirements.
- Cross Layer and Path Priority Scheduling [Chen 08]
  - Considered layer: Physical layer, MAC layer and network layer.
  - Optimization goal: Scalable video transmission over WSNs.
  - Designed new routing algorithm in network layer: Yes, DGR [Chen 07].
  - Considered Energy Efficiency: Yes, the DGR routing algorithm aims at balancing the energy consumption in the WSN.
  - Unique feature: The cross layer technique is used for adaptive coding for the source rate adjustments based on the DGR multipath routing.
- Cross Layer optimization for one shot event recording [Shu 08d]
  - Considered layer: Physical layer and network layer.
  - Optimization goal: 1) Maximize streaming data gathering in WMSNs within an expected network lifetime; 2) Minimize transmission delay for streaming data gathering in WMSNs within an expected network lifetime.
  - Designed new routing algorithm in network layer: Yes, TPGF [Shu 07a].
  - Considered Energy Efficiency: No, the proposed cross layer approach aims at providing the best system performance (maximized data gathering or minimized transmission delay) within an expected network lifetime.
  - Unique feature: The TPGF routing algorithm uses the adjusted transmission radius to explore one or multiple hols-bypassing paths.
- Context Aware Cross Layer optimization [Shu 09c]
  - Considered layer: Network layer and transport layer.
  - Optimization goal: Maximizing the gathering of the most valuable information to the base station.
  - Designed new routing algorithm in network layer: No, but still using the same TPGF routing algorithm [Shu 07a].
  - Considered Energy Efficiency: Yes, the TPGF routing algorithm always explore the shortest transmission paths.
  - Unique feature: The combination between the concept of context-awareness and cross layer optimization to facilitate the video streaming in WMSNs.
- RRA Scheme
  - Considered layer: Physical layer, network layer, and transport layer.
  - Optimization goal: Maximizing the gathering of the streaming data within an expected network lifetime.
  - Designed new routing algorithm in network layer: No, but still using the same TPGF routing algorithm [Shu 07a].

- Considered Energy Efficiency: No, the proposed cross layer approach aims at maximizing data gathering within an expected network lifetime
- Unique feature: The cross layer interaction in RRA scheme includes four steps, and the source node can adjust the data generation rate based on the information of the qualified routing paths.

Based on the above high level comparison, it is clear that the RRA scheme considers the different optimization goal from those of [Navrati 08, Tommaso 08, and Chen 08], and consequently investigates the different layers of the network protocol. RRA scheme is a more comprehensive version of the combination based on the concepts of both [Shu 08d] and [Shu 09c], in which the TPGF routing algorithm plays the core role.

6 Simulation

The proposed RRA algorithms are evaluated in a newly implemented sensor network simulator called NetTopo [Shu 07b, Shu 08b, Shu 08c, and Shu 09b]. Table 2 shows the parameters used in NetTopo for the simulation. The base station is randomly deployed in the sensor network. For any given base station with $N_{NeighborNode}$ number of 1-hop neighbor nodes within its transmission radius, it can have maximum $N_{NeighborNode}$ number of possible node-disjoint routing paths for receiving data. Thus, the number of source nodes is chosen as 8, and then every source node is guaranteed to successfully find at least 2 routing paths by using TPGF as shown in Fig.6. If a large number of source nodes are deployed, some of them may not be able to find a routing path because no relay nodes are available.

Parameter	**Value**	**Parameter**	**Value**
Network Size	500 m * 500 m	R_{min}	5 kbps
N	400	$T_{ransCapa}$	20 kbps
$S_{Source\ Node}$	8	$T_{ransCapaSour}$	60 kbps
$E_{nerSensNode}$	36 J (3 batteries)	E_{elec}	50 nj/bit
T_{Cons}	250 ms	E_{amp}	0.1 nj/bit/m^2
$D_{hop} + D_{otherfactors}$	20 ms	M_{axTR}	Not fixed

Table 2: Simulation parameters

For wireless networks with low bandwidth (less than 64 kbps), the general delay constraint of multimedia streaming data varies from 250 - 900 ms [Guide 05]. In the simulation, we adopt 250 ms as the delay constraint of the multimedia streaming data. We set the transmission capacity of sensor nodes $T_{ransCapa}$ as 20 kbps based on the RENE motes developed at UC Berkeley, which operates at 19.2 kbps [Hill 00]. In such network, the single-hop delay for a 50 byte message is about 20 ms, which is set as the average delay of each hop in the simulation. Based on the delay constraint of multimedia streaming data 250 ms and the average delay of each hop 20 ms, the maximum allowed number of transmission hops is 12. The values of E_{elec} and E_{amp} have been widely used in previous research studies [Heinzelman 00, Shin 06]. Because this radio consumption model is relatively old, interested readers can also use the latest energy consumption model based on the micaz (Crossbow) sensor node [MICAZ 09] to produce different (better) simulation results.

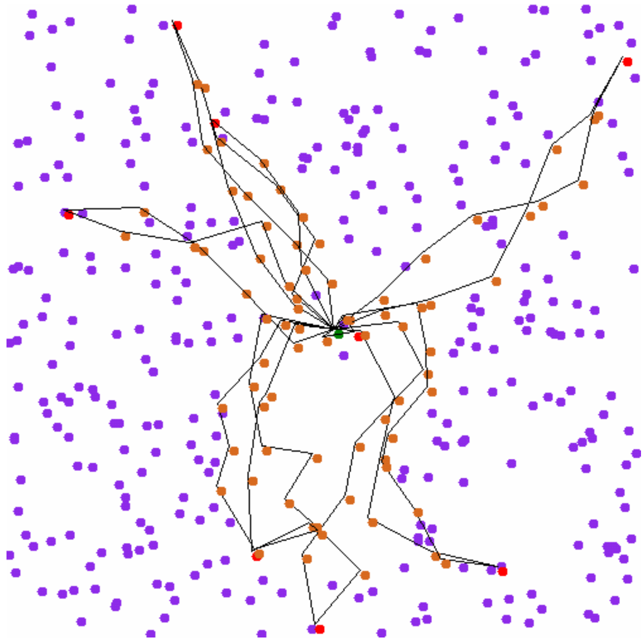

Figure 6: The simulated sensor network (M_{axTR} = 60 M): every source node can use at least two paths. The number of transmission hops of each routing path is smaller than 12. The location of the base station is randomly chosen, where the number of neighbor nodes of the base station is limited.

We simulate the sensor network with different physically allowed maximum transmission radius M_{axTR}: 60 m, 70 m, 80 m, and 90 m. Four important parameters are chosen to reflect the RRA performance: 1) Total gathered data D, which can reflect the efficiency of RRA algorithms for streaming data gathering; 2) Maximum data generation rate R_{max}, which can demonstrate the adjusted data generation rate R by using RRA algorithms; 3) Number of total relay nodes, which can show the number of routing paths; 4) Average end-to-end transmission delay, which can reflect the actually used transmission radius (either $M_{axTR\ or}\ E_{xpTR}$) when the expected network lifetime changes.

Fig.7 shows the total gathered data in the base station in term of the expected network lifetime. The legend “Original Gathering” in Fig.7 shows the gathered data without using RRA. It is clear that RRA strategy can significantly increase the amount of gathered data. Furthermore, smaller M_{axTR} can achieve more potential in increasing the amount of gathered multimedia data. For example, in case of M_{axTR} = 60 m, the allowed increasing space can exist until the expected network lifetime is 14 hours. In case of M_{axTR} = 90 m, the allowed increasing space can only exist until the expected network lifetime is 11 hours.

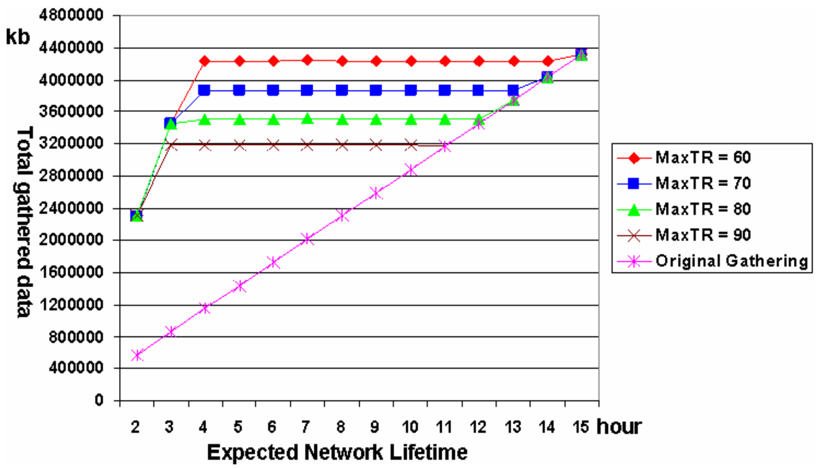

Figure 7: Total gathered data D VS. Expected network lifetime

Fig.8 shows the adjusted R_{max} in terms of the expected network lifetime. When the expected network lifetime is only two hours, R_{max} is bounded by the physically allowed maximum transmission capacity $T_{ransCapa}$. The two routing paths of each source node as shown in Fig.6 are fully utilized. When the expected network lifetime changes into 15 hours, in four different situations, all the routing paths transmit multimedia streaming data with 5 kbps, which is the minimum data generation rate R_{min}.

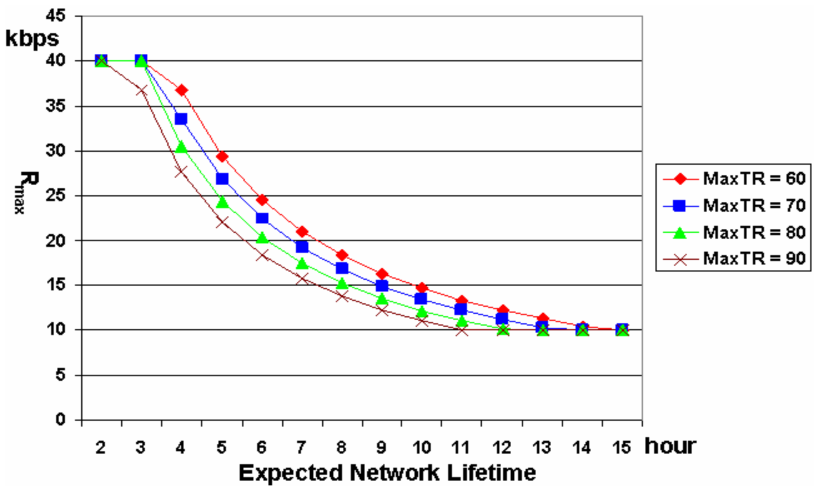

Figure 8: Maximum data generation rate R_{max} VS. Expected network lifetime

Fig.9 shows the number of relay nodes in terms of the expected network lifetime. When the expected network lifetime is as short as only 2 hours, two routing paths are needed, which nearly doubles the number of relay sensor nodes. From Fig.8, when the expected network lifetime increases to 15 hours, in four different situations, the number of relay nodes keeps unchanged. This means that the identical E_{xpTR} is actually used for transmission. We can also see that for M_{axTR} = 60 m, the number of relay nodes with the expected network lifetime $E_{xpeLifeTime}$ = 15 hours is a little larger than the number of relay nodes with the expected network lifetime $E_{xpeLifeTime}$ = 14 hours. This indicates that E_{xpTR} is smaller than 60 m when the expected network lifetime $E_{xpeLifeTime}$ is 15 hours.

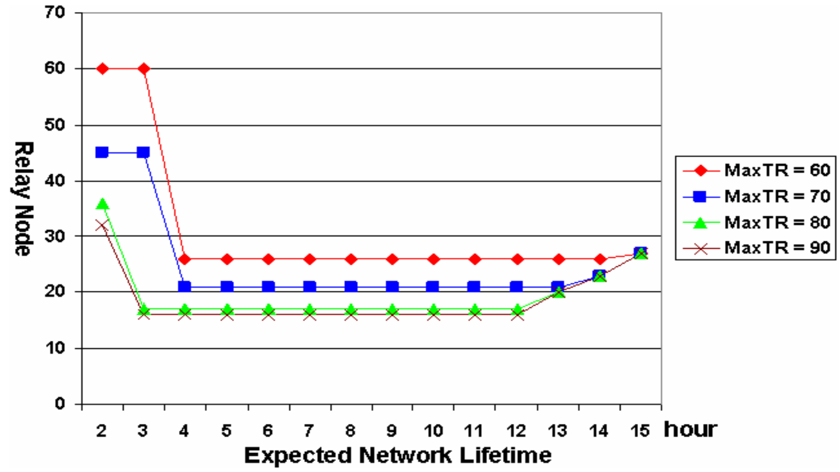

Figure 9: Number of total relay nodes VS. Expected network lifetime

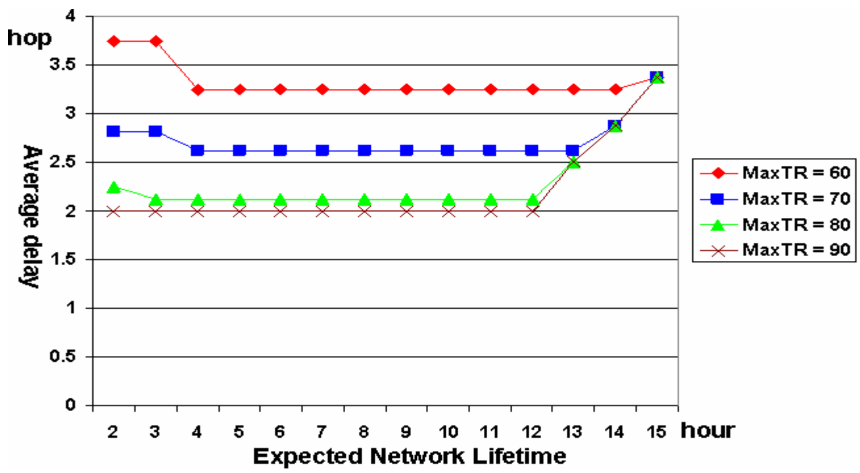

Figure 10: Average end-to-end transmission delay VS. Expected network lifetime

Fig.10 shows that a shorter M_{axTR} leads to a longer average transmission delay and a longer expected lifetime also leads to a longer average transmission delay. When M_{axTR} = 60 m, 70 m, and 80 m, and the expected network lifetime is 2 hours, the average delay is a little longer than that of other situations such as the expected network lifetime is 4, 5, … 12 hours. The reason is that two routing paths are used for transmission. Among these two routing paths, the second path may be longer than the first path, which finally increases the average end-to-end transmission delay.

In Fig.10, for all of four different situations, the average end to end transmission delay is increased when the expected network lifetime increases, e.g. in the case of M_{axTR} = 90 m, the end-to-end delay increases from 2 to 3.375 when the expected lifetime increases from 12 to 15 hours. The increasing delay shows that the used transmission radius is changed from M_{axTR} to E_{xpTR}. In addition, E_{xpTR} reduces with greater network lifetime.

7 Conclusion

In this paper, we focus on efficient data gathering scheme in wireless multimedia sensor networks. The interested applications include volcano eruption or a battlefield in frontline, wherein the WSNs are not deployed to work for an extremely long time but to deliver continuous multimedia data as much as possible within an expected lifetime. The identified research problem is formulated as maximizing the total gathered data in a base station and minimizing the end-to-end transmission delay in a WSN within an expected lifetime. Two distributed transmission Radius and data generation Rate Adjustment (RRA) algorithms are proposed to solve this problem. Simulation results show that RRA strategy can effectively solve the problem and improve the data gathering performance in the identified scenarios and applications.

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