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Adaptive Optimization of Multi-Hop Communication Protocol for Linear Wireless Monitoring Networks on High-Speed Railways

Xiao-Ping Ma, Hong-Hui Dong, Peng Li, Li-Min Jia, Xiang Liu, Yong Qin, and Jun-Qing Tang

***Abstract*— The multi-hop communication protocol can balance the energy consumption of sensors to extend the service lifetime in high-speed railways (HSRs). However, the communication via multiple hops will increase the data transmission latency. Most previous studies have focused on optimizing either the sensor network lifetime or the data transmission latency but have not considered both. This paper presents an adaptive multi-objective optimization model for multi-hop communication systems. This model explicitly addresses the trade-off between the lifetime and the latency associated with the use of network-level wireless condition monitoring systems for ensuring the railway operational safety. Numerical examples with various operational scenarios are developed to demonstrate the superiority and practicality of the proposed approach. Compared with the three previously applied protocols, the proposed approach can achieve longer sensor network lifetime, shorter data latency, and greater system utility (accounting for both lifetime and latency). This paper provides the technical support for the development of stable and reliable wireless monitoring management systems for HSR safety.**

***Index Terms*— High speed rail, wireless monitoring system, multi-hop, scheduling optimization, lifetime, latency.**

I. Introduction

WITH the rapid increase of operating speed and mileage, how to tackle infrastructure failures is becoming more important for worldwide high speed railway (HSR) systems. The infrastructure failures may cause train accidents, traffic delay, or economic loss [1], [2]. Studies have shown that the safety of railway system can be significantly improved by inspecting the infrastructure conditions in real time [3], [4]. The on-line monitoring systems have been applied to inspect the service condition and transmit the information to the data base station for failure diagnosis. The cable communication network has been verified more stable and reliable. However, the operational environment of the railway is so complex that the power supply and cable communication network are impracticable, and the system construction cost is very high. Hence, wireless systems are usually adopted to monitor the railway service conditions [5], [6]. However, the energy storage capacity, information processing ability and communication bandwidth of wireless communication units are limited [7]. It is vital but challenging to ensure the continuous, reliable and timely transmission of the railway infrastructure condition information and the energy-efficiency of the system [8]. Thus, an improved protocol is required to make better use of the limited energy and extend the lifetime of the wireless condition monitoring system. However, the different distances between the origin and destination communication units may result in unbalanced energy consumption among all sink nodes and thus may shorten the system lifetime. Meanwhile, the prompt data transmission should be ensured for the timely transmission of safety-critical information. Practically, it is difficult to ensure the prompt data transmission and maximize the sensor lifetime simultaneously. In particular, putting higher priority on the lifetime may increase the number of hops and thus will delay the transmission of the outburst incident, which may cause serious accidents. Hence, the protocol optimization for both the lifetime and timely transmission is of great practical relevance and thereby deserves further research.

In intelligent HSR systems [9], wireless monitoring can be decomposed into information apperceiving, transmitting, processing, state evaluating & forecasting, and decision-making [10]. Two essential issues should be addressed when designing the communication protocols. First, the transmission structure to support the routing plan and energy-consumption modeling should be determined. Second, the lifetime and real-time demands of the monitoring objects in HSR should be analyzed in advance. Generally, the multi-hop communication

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TABLE I
SUMMARY OF THE LITERATURE ON THE OPTIMIZATION OF THE WIRELESS NETWORK PROTOCOLS

Authors	Optimization Objective	Evaluation Indexes	Network Structure	Communication Protocol	Methodology
S. Bhattacharjee, and S. Bandyopadhyay (2013)	Lifetime Maximization	System lifetime	Linear network structure	Multi-hop protocol	Minimize the total energy consumption of all nodes (MTEC)
R. Kacimi, R. Dhaou, and A. L. Beylot (2013)	Lifetime Maximization	System lifetime	Linear network structure	Multi-hop protocol	Minimize the maximum energy consumption of all nodes (MMEC)
J. H. Lee (2015)	Lifetime Maximization	System lifetime	Linear network structure	Multi-hop protocol	Minimize the variance of the energy consumption among all nodes (MVEC)
M. Elhoseny, *et al*. (2015)	Lifetime Maximization	System lifetime	Mesh network structure	Cluster-based protocol	Balancing Energy Consumption in Heterogeneous Wireless Sensor Networks Using Genetic Algorithm
G. M. Shafiullah, S. A. Azad, and A. B. M. Shawkat Ali (2013)	Lifetime Maximization	System lifetime and latency	Linear network structure	Schedule-based protocols	Adjust the state of the nodes according to the allocated time slot (EA-TDMA and E-BMA) to minimize the energy consumption
J. C. Ma, W. Lou, and X. Y. Li (2014)	Lifetime Maximization	System lifetime and latency	Tree network structure	Schedule-based protocols	Utilize the contiguous link scheduling strategy to reduce the energy consumption caused by nodes' state transitions
Y. S. Yun, *et al* (2013)	Lifetime Maximization	System lifetime and latency	Tree network structure	Schedule-based protocols	Find an interference-free link scheduling with the minimum number of time slots used and reduce the energy consumption in idle state
X. H. Xu, *et al* (2009)	Latency Minimization	System latency and lifetime	Tree network structure	Multi-hop protocol	Propose collision-free schedule for data aggregation in WSNs to minimize the latency
L. J. Guo, Y.s. Li, and Z. p. Cai (2016)	Latency Minimization	System latency and lifetime	Tree network structure	Multi-hop protocol	Propose an energy-efficient distributed scheduling algorithm named Clu-DDAS based on a novel cluster-based aggregation tree to minimize latency

protocols are especially applicable to the linear transmitting structures such as railways monitoring system [11]. Multi-hops aim to prolong the system lifetime by offsetting the unbalanced energy consumption due to different distances between the sink nodes and the base station. However, excessive hops will increase the latency of data transmission, and thus delay the real-time transmission of safety-critical information and affect the system safety. Therefore, it is pivotal to design an optimal multi-hop communication protocol to make a better trade-off between the system lifetime and latency of railway wireless monitoring system. To this end, this paper aims to develop an adaptive optimization method that can meet various demands for the condition monitoring of different railway infrastructure components simultaneously.

Table I presents typical existing studies in terms of the optimization objectives, evaluation indexes and corresponding methodologies. Most of them focus on maximizing the system lifetime. They can be categorized as optimization for node deployments [12], data packets pre-processing [13], transmission power adjustment [14], and communication protocols design [15]. Among them, the protocols optimization has been proved to be more effective and extensively applied. The protocols optimization algorithms could be classified into single-hop [16], multi-hop [17] and cluster-based [18], [19] strategies according to various structures of the objects. For the linear railway communication networks, the multi-hop protocols are more appropriate [20]. Some studies have utilized the multi-hop protocols to maximize the lifetime of monitoring system by minimizing the total energy consumption (MTEC) [21], [22]. However, it may cause the unbalance of the energy consumption among all sensors, and incur some nodes failure or even decrease the system lifetime. Some other studies have tried to balance the energy consumption among all nodes by minimizing the maximum energy consumption (MMEC) [23], or minimizing the variance of energy consumption (MVEC) among all nodes [24]. In the multi-hop protocols, there is a positive correlation between the number of hops and the communication latency. Furthermore, these algorithms focus on balancing the energy consumption among all the nodes, whereas the minor imbalance in energy consumption among all sink nodes will lead to the unbalance in the residual energy among the nodes after several transmission rounds. The energy consumption of the nodes is based on the residual energy, so the schemes for balancing the residual energy have been proved more effective [25], [26].

To the best of our knowledge, there are few studies related to minimum-latency algorithm (MIA) for railway monitoring systems. Recently, an efficient distributed method using collision-free schedule for data aggregation was proposed to minimize the latency [27], and a novel cluster-based aggregation tree was adopted then [28]. Further, some studies on MIA consider the data arrogation in the tree-structure network, but the complex structure decreases the efficiency in the actual linear railway monitoring system. Moreover, most results related to the latency usually take the service lifetime as the sole optimization objective and use the time delay as the evaluation index [29]–[31]. Schedule-based strategies can configure the multi-hops well to resist the system latency, but limited prior studies have considered both the lifetime and data latency of wireless condition monitoring system simultaneously via a multi-objective model and bi-criteria evaluation index of system utility [32]. These problems are addressed in this work.

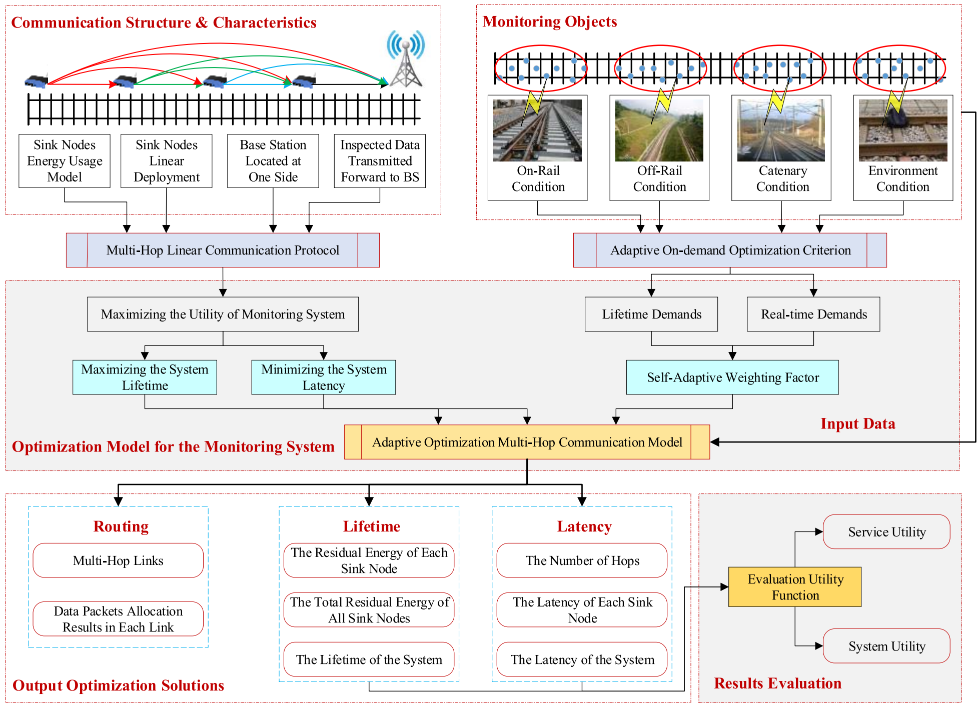

Fig. 1. Overall Scheme of the Adaptive Multi-Hop Communication Protocol for Railway Monitoring System.

II. Motivation

The power supply and cable network construction for the railway in the remote area are always difficult or the cost is very huge. In contrast, the wireless communication system is effective to transmit the inspection information for the railways. However, wireless nodes have limited energy for information transmission, and railway systems place an intensive demand for the real-time communication of the monitoring objects. It is necessary to consider the lifetime and latency of the communication systems. Motivated by the above description and the literature review observations, this paper proposes an adaptive multi-objective optimization model and a novel evaluation scheme for the multi-hop protocol. The key contributions of this work can be summarized as follows.

(1) A comprehensive utility evaluation mechanism considering both the service lifetime and latency is proposed. It demonstrates superiorities compared to most existing methods with single optimization objective and indicator evaluation. This ensures higher efficiency and applicability for complex railway monitoring systems.

(2) The priorities of lifetime and real-time demands are classified, and a self-adaptive control parameter is adopted for different service priorities. Most existing studies on railway infrastructure monitoring focus on a particular or homogeneous object (e.g., track [33], rail bed [34], pantograph [35], etc.) in a certain optimization model, which can hardly satisfy the varying requirements of multiple components in an HSR system.

(3) Considering that few studies are related to the latency stemmed from the multi-hops, this study uses a multi-hop scheduling algorithm to reduce the time delay given the quantity of multi-hops. This satisfies the real-time requirement of transmitting emergency and urgent safety-related information for railways.

The remainder of this paper is organized as follows. Sec. III displays the typical monitoring objects and the corresponding requirements of the railway system, and depicts the overall scheme. In Sec. IV, the multi-hop optimization model is described in detail. Performance measures of the protocol are introduced in V. The empirical validation and discussions are presented in Sec. VI. The conclusions are summarized in Sec. VII, and some future research issues are discussed in Sec. VIII.

III. System Profile and Overall Scheme

As shown in Fig.1, the system is composed of five modules: 1) communication structure & characteristics; 2) monitoring objects; 3) optimization model for the monitoring system; 4) output optimization solutions, and 5) results evaluation.

A. Communication Structure and Characteristics

A railway wireless monitoring system has many sensors installed along the railway line for monitoring the service condition of the infrastructures and the operating environments. The monitoring and communication system has similar structure to the rail and can be roughly considered as a linear network.

In the linear transmitting system, the base station is located at the end of some monitoring regions, while the sink nodes are deployed evenly along the rail. The inspection information is collected by the sink nodes and then transmitted forward to the nearest base station. The energy dissipation model shows that the energy consumption of the sink nodes is related to the size of data packets and longer distance renders more

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TABLE II
THE MONITORING OBJECTS AND CORRESPONDING LIFETIME & REAL-TIME DEMANDS

Monitoring objects		**Monitoring Method**	**Lifetime demands**	**Real-time demands**
On-rail condition	Rail Longitudinal Stress	Ultrasonic guided wave technology	0.7	0.3
	Rail displacement and creeping	Displacement and creeping sensor	0.7	0.3
	Rail integrity	Ultrasonic guided wave technology	0.5	0.5
	Rail wear	Machine vision	0.4	0.3
	Rail turnout and expansion rail joint	Fiber grating strain sensor	0.7	0.7
	Rail rigidity	Mobile load test car for dynamic rail inspection	0.3	0.4
	Rail intrusion	Monocular/binocular camera video detection technology	0.9	0.7
Off-rail condition	Railway foundation settlement	Leica total station monitoring system	0.5	0.1
	Railway slope steady state	Vehicle-borne laser-scanner and fiber grating array sensor	0.5	0.6
Railway traction substation equipment and catenary	Railway tractive power supply system	Non-contact infrared temperature; fire detector; the temperature and humidity sensor, etc..	0.9	0.9
	Railway catenary safety condition	Accelerometer sensor, ratchet deviation angle sensor, temperature sensor of cable cleat	0.7	0.9
	Railway catenary tension, elasticity and vibration	Contact wire and catenary tension-measuring sensor; Contact wire vibration-measuring sensor; Catenary elasticity-measuring sensor	0.6	0.5
	Railway catenary online inspection equipment	The pantograph arc measuring device and high-precision machine vision	0.5	0.7
	Railway pantograph image recognition	Video and image acquisition and processing technology	0.9	0.7
Railway operation environment	Geological disaster monitoring	Seismometers, landslides and mudslides detection	0.3	0.1
	Severe weather monitoring (snows, hazy, rain, sand)	Laser detection equipment; video and image acquisition and processing technology	0.1	0.9
	Conventional weather monitoring (wind, temperature)	Anemorumbometer, temperature and humidity sensor	0.9	0.9

Notes: The classification and the demands of the monitoring objects are based on the National High Technology Research and Development Program of China (863 Program: No. 2011AA11A102).

energy consumption. An energy-efficiency protocol is required to meet the lifetime demands with the limited energy resources for the railway wireless monitoring system.

B. Monitoring Objects

The monitoring objects in the railway systems can be grouped into four categories: on-rail condition, off-rail condition, catenary condition, and railway operation environments condition. There are various monitoring services for each category with different monitoring methods, transmitting ways, data types & volume, and communication demands for each service. To improve the performance of the monitoring system, an adaptive criterion is considered.

The monitoring objects and corresponding characteristics are listed in Table II. The lifetime and real-time demands of the monitoring objects are all defined according to the characteristics of the monitoring objects, and the data is a relative value. The value is assigned based on the urgency degree of the inspection information transmission, which will affect the railway safety operation and should be assigned higher real-time demands. Otherwise, it will be assigned higher lifetime demands.

The lifetime and real-time demands of the monitoring objects are divided into five levels: very high (0.9), high (0.7), medium (0.5), low (0.3), and very low (0.1), according to the characteristics of the monitoring objects. For safety operation of the railway system, the real-time demands are higher than the lifetime demands. However, the energy storage of the wireless monitoring system is limited, and the lifetime of the system will affect the collection of the service condition information. Hence, in this paper, we define the real-time and lifetime demands respectively according to the characteristics of the monitoring objects, so that the monitoring system can collect more information and the key information can be transmitted immediately. Most on-rail and off-rail detections on conditions of the rail and foundation vary gradually. Thus the lifetime demands are higher while real-time demands are lower. However, the intrusions are always unexpected and hazardous, and this renders higher continuity and real-time demands. Considering the significance of the railway power supply, the condition of the railway traction substation equipment and catenary should be inspected uninterruptedly and maintained in time to avoid serious accidents caused by power system failures. In this case, the continuity and on-time demands place a higher priority. Besides, the environment is also vital to the safe operation of the railway system. The geological disaster and severe weather are potentially harmful, whose real-time demands should be higher while the continuity demands can be compensated using conventional weather monitoring methods.

C. Optimization Model for the Monitoring System

The optimization model of the monitoring system is designed to improve the performance of the wireless monitoring network. The model should involve the structure of the communication system, the types and demands of the monitoring services, and the characteristics of inspection data.

From Fig.1, we can see that: 1) Based on the structure of the railway wireless monitoring network, the multi-hop linear communication protocol is selected to optimize the routing plan. For the energy-limited wireless network, the lifetime of the system is the vital factor for collecting more infrastructure service information. In this paper, minimizing the total energy consumption and balancing them among all sink nodes

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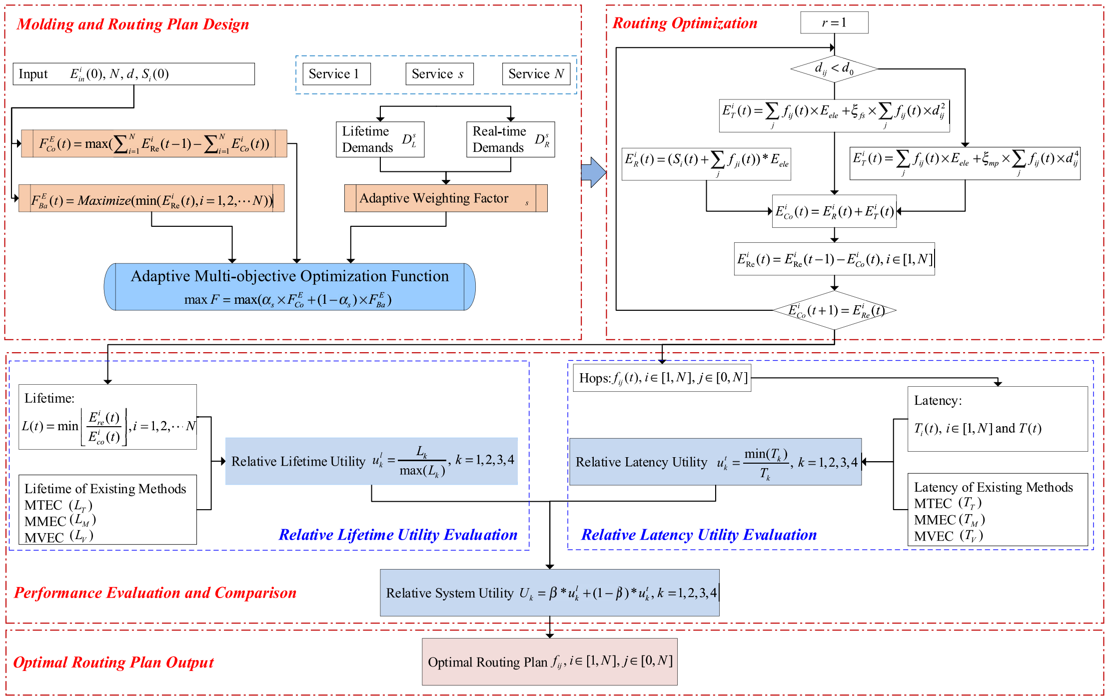

Fig. 2. Framework for Adaptive Optimization of Multi-Hop Communication Protocol.

are considered simultaneously to extend the system lifetime; 2) By analyzing the characteristics of the monitoring objects in the railway system, self-adaptive control parameters are designed for various demands of all services; 3) the adaptive optimization multi-hop communication model is proposed by combining the above two factors, so that the construction is optimized with varying monitoring and transmitting objects intelligently and adaptively.

D. Optimization Solutions

The output solutions include three parts: 1) the routing plans, for determining the multi-hop links and the size of the data packets in each link; 2) the lifetime related information, such as the total/individual residual energy of the sink nodes and the system lifetime; 3) the latency related information, such as the number of multi-hops and the latency of each system service respectively.

E. Results Evaluation

The performance of the proposed protocol will be evaluated by a multi-criteria utility function. The latency and lifetime utilities are generated based on the corresponding solutions. Furthermore, the relative system utility is designed based on the two utilities. The performance of the proposed protocol is compared with other protocols.

IV. Molding and Methodology of the Multi-Hop Protocol

In this section, the adaptive optimization multi-hop communication model is proposed based on the principles of maximizing the system lifetime and satisfying the demands of all the service adaptively, as shown in Fig.2.

For the linear railway wireless monitoring system, the lifetime is vital for collecting the infrastructure & operation

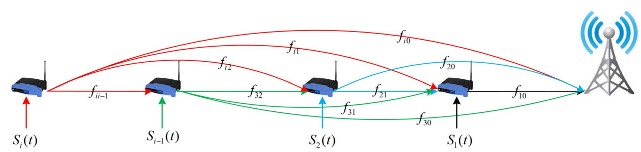

Fig. 3. The Structure of Multi-Hop Communication Protocol.

environment information as much as possible for fault diagnosis and predictive risk management. Meanwhile, real-time information transmission capability is also needed for the emergency incidents or the safety-related services whose information should be transmitted immediately. The parameters used in this paper are listed in Table III.

To maximize the utility of the system, we try to maximize the lifetime and minimize the latency simultaneously. Hence, two objective functions are involved. One is F_{Co}^E, which is used to minimize the energy consumption to reduce the number of hops, and then decline the latency. The other one is F_{Ba}^E, which is used to balance the energy consumption, and thus extend the lifetime. The multi-objective function is then formulated as follows, and the parameters in the formula are listed at the end of this paper.

$$\max F = \max(\alpha \times F_{Co}^E + (1-\alpha) \times F_{Ba}^E) \tag{1}$$

where α is the adaptive weighting factor to adjust the impactor of the two parts for the aggregated objective function. This parameter is related to the demands of the monitoring and transmitting services. Each part of the optimization function will be designed in the following parts.

The multi-hop communication protocol, as described in Fig.3, has N sink nodes ($index\ 1, 2, \cdots N$) and one base station ($index\ 0$) deployed in the railway wireless monitoring system. Each sink node collects the information from the sensor layer ($S_i(t),\ i = 1, 2, \cdots N$) and then transmitted to the

TABLE III
PARAMETERS LIST USED IN THE MODELS

Parameters	Representation
α	Adaptive weighting factor
i	Serial number of the source sink node, $i = 1, 2, \cdots, N$
j	Serial number of the destination node, $j = 0, 2, \cdots, N-1$
0	Serial number of the base station
f_{ij}	The transmitting hops from the ith node to the jth node
N	The total number of the sink nodes
$E^i_{\text{Re}}(t-1)$	The residual energy after $t-1$ communication rounds of ith sink node
$E^i_{\text{Co}}(t)$	The energy consumption at tth communication round of ith sink node
$E^i_R(t)$	The energy consumed for receiving the data packets by the ith sink node at the tth round
$E^i_T(t)$	The energy consumed for transmitting the data packets forward by the ith sink node at the tth round
$S_i(t)$	The size of the data packets received from the sensor layer by the ith sink node at the tth round
E_{ele}	The energy consumption of the circuit to process 1bit data
ξ_{fs}	Amplifier energy coefficient (d^2)
ξ_{mp}	Amplifier energy coefficient (d^4)
E^i_{Initial}	The initial energy of the sink node i
D^s_T	The lifetime demands for the sth service
D^s_R	The real-time demands for the sth service
η	The amplification coefficients for the lifetime demands
ξ	The amplification coefficients for the real-time demands
T_i	The latency of ith service
T	The system latency
k_i	The number of hops from ith sink node
r_{im}	The mth multi-hop routing from sink node i to the base station
h_{ij}	The number of the hops from ith sink node to jth sink node
T_{aj}	The arrival time at the jth sink node
p	The label of the relay node from the source sink node to the base station
q	The label of the last relay node from the source node to the base station
β	The coefficient to adjust the importance of lifetime and latency utility
u^l_k	The lifetime utility of kth compared protocol
u^t_k	The latency utility of kth compared protocol
k	The index of the compared protocols, $k = 1, 2, 3, 4$

base station in the end. The multi-objective is accomplished by optimizing the routing matrix in Eq. (2), which represents the multi-hop links between the sink nodes and the corresponding transmitted data packets size. The lifetime of the system will be improved with the optimal matrix.

$$G = \begin{bmatrix} f_{N,N-1} & \cdots & f_{N,j} & \cdots & f_{N,0} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & f_{i,j} & \cdots & f_{i,0} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & f_{1,0} \end{bmatrix} \tag{2}$$

where, N represents the number of the sink nodes; $f_{i,j}$ indicates the communication links from the i th node to j th node, and its value implies the data packet size transmitted in the link.

A. Minimizing the Total Energy Consumption

For the wireless monitoring system with limited energy, the lifetime is mostly affected by the energy consumption of the system, while the less energy consumption renders longer lifetime. The system energy consumption is the sum of the energy consumed by all the sink nodes receiving and transmitting data packets. Assuming that there are N sink nodes deployed in line, we collect the information transmitting from the sensor layer to the base station. We then assume that the initial energy of the sink nodes is equal, and thus minimizing the total energy consumption is equivalent to maximizing the total residual energy of all sink nodes, as

$$F^E_{Co}(t) = \max\left(\sum\nolimits_{i=1}^{N} E^i_{Re}(t-1) - \sum\nolimits_{i=1}^{N} E^i_{Co}(t)\right) \tag{3}$$

The energy consumption of each sink node arises from data receiving and transmitting. The energy consumption model based on the multi-hop protocol for the linear communication system is defined as

$$E^i_{Co}(t) = E^i_R(t) + E^i_T(t) \tag{4}$$

where $E^i_R(t)$ is the energy consumed for receiving the data packets, denoted as

$$\begin{aligned} E^i_R(t) &= (S_i(t) + \sum_j f_{ji}(t)) * E_{ele} \\ &S.T.\ i < j, i \in [1, N], j \in [2, N] \\ &f_{ji}(t) \geq 0\ for\ i < j \\ &f_{ji}(t) = 0\ for\ i \leq j \end{aligned} \tag{5}$$

The first constraint implies that the data packets are transmitted forward to the base station. The second and third constraints ensure that the size of the segmented packets is nonnegative.

The $E^i_T(t)$ is the energy consumed by the $i-th$ sink node for transmitting the data packets at the $t-th$ round [36], as

$$\begin{aligned} E^i_T(t) = &\begin{cases} \sum\limits_j f_{ij}(t) \times E_{ele} + \xi_{fs} \times \sum\limits_j f_{ij}(t) \times d^2_{ij}, & d_{ij} < d_0 \\ \sum\limits_j f_{ij}(t) \times E_{ele} + \xi_{mp} \times \sum\limits_j f_{ij}(t) \times d^4_{ij}, & d_{ij} > d_0 \end{cases} \\ &S.T.\ i > j, i \in [1, N], j \in [0, N] \\ &\quad f_{ij}(t) \geq 0, \quad for\ i > j \\ &\quad f_{ij}(t) = 0, \quad for\ i \leq j \end{aligned} \tag{6}$$

The first constraint implies that the data packets are transmitted forward to the base station, the second and third constraints indicate that the size of the segmented packets is nonnegative.

For each sink node, the input size of the data packets is equal to the output ones, which means that no data packets are generated or disappeared during the communication process, as

$$\sum_j f_{ij}(t) = \sum_j f_{ji}(t) + S_i(t), \quad i \in [1, N] \tag{7}$$

The residual energy of the sink node i is calculated as

$$E^i_{Re}(t) = E^i_{Re}(t-1) - E^i_{Co}(t), \quad i \in [1, N]$$
$$E^i_{Re}(0) = E^i_{\text{Initial}}, \quad i \in [1, N] \tag{8}$$

where the E^i_{Initial} is the initial energy of the sink node i, and it is constant and determined once installed in the monitoring module.

B. Balancing the Energy Consumption

In the linear wireless railway infrastructure monitoring system, each sink node transmits the data collected from the sensor layer in a certain monitoring area, and any invalid sink node may lead to the communication breakdown and even inspection failures. Most energy of the sink nodes is dissipated during the transmission of the data packets. Furthermore, as shown in Eq.(6), the transmission energy depends on the volume of the packets and communication distances. The great differences in the distances among the sink nodes and the base station may lead to unbalanced energy consumption and even shorten the system lifetime. Hence, in addition to minimizing the total energy consumption, the communication protocol should be improved as well to balance the energy consumption among sink nodes.

As shown in Eq.(8), the data packets transmission and energy consumption are all carried out based on the residual energy of the previous round. Maximizing the minimal residual energy is more reasonable compared with balancing the energy consumption of all sink nodes. The optimization model is designed as

$$F^E_{Ba}(t) = Maximize(\min(E^i_{Re}(t), i = 1, 2, \cdots N)) \tag{9}$$

Maximizing the minimal residual energy could improve the lifetime of the sink node with the maximum energy consumption, and extend the lifetime of the system effectively.

C. Adaptive Weighting Factor

The performance of system lifetime and the number of communication hops will be different with varying adaptive weighting factors in (1). The correlation between the number of hops and service/ system latency is shown as follows.

As shown in Table I, the lifetime and real-time demands are various for different monitoring services. To improve the self-adaptive capability of the proposed model and satisfy the requirements of different services, the adaptive weighting factor is presented. The applicability and feasibility are considered during the design process of α. When the real-time demand is less than 0.5 ($D^s_T < 0.5$), corresponding to the weak urgency of the service, and the model focuses on extending the system lifetime and α will increase greatly with the increasing lifteime demands. Otherwise, the monitoring objects may be unexpected incidents or safety-related services whose real-time demands are high when $D^s_T > 0.5$, and then the real-time demands should be given the priority and thus α increases gradually before the lifetime demands reach the upper limit. We herein select the middle value of the two models for α_s when $D^s_T = 0.5$. The relationship between the demands and the weighting factor is nonlinear, meantime, the real-time demand should be satisfied in advance. With these criteria, the adaptive weighting factor is designed as,

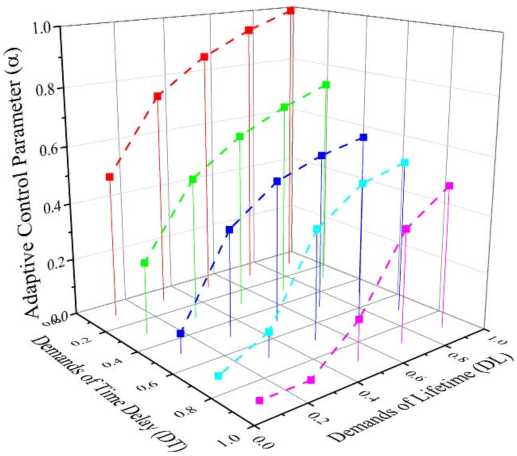

Fig. 4. The varying adaptive weighting factor.

$$\alpha_s = \begin{cases} \dfrac{\log(\eta \times ({D^s_R}/{D^s_T}))}{\log(\eta \times \max({D^s_R}/{D^s_T}))}, & D^s_T < 0.5 \\[2ex] \dfrac{0.5 \times \log(\eta \times ({D^s_R}/{D^s_T}))}{\log \max(\eta \times {D^s_R}/{D^s_T})} + \dfrac{0.5 \times 1}{1 + e^{\frac{(D^s_R - D^s_T) \times D^s_T}{(\xi - (D^s_R - D^s_T)) \times D^s_R}}}, & D^s_T = 0.5 \\[2ex] \dfrac{1}{1 + e^{\frac{(D^s_R - D^s_T) \times D^s_T}{(\xi - (D^s_R - D^s_T)) \times D^s_T}}}, & D^s_T > 0.5 \end{cases} \tag{10}$$

Herein, α_s is the adaptive weighting factor for the $s-th$ service. It increases with increasing the lifetime demands and declining of the real-time demands. The varying adaptive weighting factor indicated by (10) is shown in Fig.4.

For the railway infrastructure wireless monitoring system, when the service is not urgent, the lifetime should be placed the highest priority. The amplification factor η is introduced as

$$\eta = \frac{\max D^s_R}{\min D^s_T}, \quad 0 < D^s_R < 1, \ 0 < D^s_T < 0.5 \tag{11}$$

The parameter ξ is used to guarantee the real-time demands, defined as

$$\xi = \max(D^s_T - D^s_R), \quad 0 < D^s_R < 1, \ 0.5 < D^s_T < 1 \tag{12}$$

D. Minimizing the Latency

To resist the interferences, the Time-Division Multiple Access (TDMA) protocol is usually adopted in the wireless monitoring system to optimize the orders of the multi-hop links to minimize the latency. For this protocol, the communication of each unit (sink node or base station) is divided into several frames and then divided into several time-slots according to the number of links (in and out). For the multi-hop communication system, many communication links (hops) are caused by the data transmitting among the sink nodes and the base station. To minimize the latency by optimizing the hops schedule, we make some assumptions according to the field investigations and actual communication mechanism of the TDMA in the following:

a. The data packets are all transmitted towards the direction of the base station;

b. The data packets of each sink node are sent just after all the receiving actions are completed;

c. At each time-slot of any communication unit, only one action (receiving or sending) is carried out;

d. The sink nodes are just in charge of data packets receiving and transmitting without data processing;

e. Each sink node transmits the data packets of a certain kind of service;

f. The latency of a specific service is defined as the number of time-slots consumed when all of its data packets arrive at the base station;

e. The system latency is equal to the maximum latency of all services.

In Step 1, the number of communication links from the sink nodes is recorded;

In Step 2, the whole communication links from each sink node to the base station are recorded;

In Step 3, the communication order of the links from the first sink node is arranged, and the communication serial numbers are assigned to the links;

In Step 4, the maximum serial number of the communication links to the sink node is recorded as the current arrival time at this sink node;

In Step 5, the communication order of the links for other sink nodes are all arranged, and the communication serial numbers are all assigned correspondingly;

In Step 6, the maximum serial number of the communication links to the base station is recorded as the system latency;

In Step 7, the arrival time for all the communication links is calculated;

In Step 8, the maximum arrival time for each sink node is recorded as the latency.

V. Performance Measures of Protocol

To analyze the performance of the proposed Adaptive Utility Maximization Protocol (AUMP) for the linear railway monitoring system, we compare its performance with other existing protocols with the objectives of minimizing the total energy consumption (MTEC), minimizing the maximum energy consumption (MMEC), and minimizing the variance of the energy consumption (MVEC). The performance measures include the hops, latency, lifetime, and relative utility of the system. Note that the latency and relative utility have been rarely considered in previous studies.

A. Hops of the Monitoring System

The inspection information is transmitted among the sink nodes and finally reaches the base station, as shown in Fig.3. The unbalance of the energy consumption caused by the different distances from different sink nodes to the base station could be offset using the multi-hop communication protocol. Note that excessive hops will lead to system latency increase, which is not tolerable for the emergency demand in railway. The number of hops varies due to the changing number or distance between the sink nodes and size of the transmitted data packets. The hops will be used to estimate the latency of the monitoring system as follows.

B. Latency of the Monitoring System

The failure of the railway system infrastructure might cause serious accident. Hence, it is necessary to transmit the safety related data to the database as soon as possible, and the communication latency should be reduced for the critical monitoring objects. The system and service latency are optimized and calculated as shown in Table III.

C. Lifetime of the Monitoring System

For the railway monitoring system, the inspection data packets are transmitted from the sink nodes to the base station in multiple rounds. The system lifetime is defined as the number of communication rounds when the first sink node fails due to the energy exhaustion. In this paper, it is assumed that all sink nodes have the same initial energy. The system will communicate in a stable structure once it is determined. The remaining lifetime of the system at $t-round$ is defined as the minimum communication rounds of all sink nodes, as

$$L(t) = \min \left\lfloor \frac{E_{Re}^{i}(t)}{E_{Co}^{i}(t)} \right\rfloor, \quad i = 1, 2, \cdots N \tag{13}$$

where $\lfloor \bullet \rfloor$ represents the maximum integer no larger than $\bullet$. The lifetime of the system could be calculated when $t = 0$.

D. Relative Utility of the Monitoring System

The performance of the railway infrastructure monitoring system is determined by both of the lifetime and latency. To synthetically evaluate the efficiency of the system and compare the performance with other three traditional protocols, the relative utility is defined as

$$U_k = \beta \times u_k^l + (1-\beta) \times u_k^t, \quad k = 1, 2, 3, 4 \tag{14}$$

where k is the index of the protocols to be compared; β is the coefficient used to adjust the effects of the two utilities. The railway wireless monitoring system aims to monitor the railway condition continually while lowering the frequency of emergencies. Hence, the lifetime demands are more important than the real-time demands from an overall view. In this paper, we set $\beta = 0.7$ for simulation illustration; u_k^l is the relative utility function of lifetime, and u_k^t is the relative utility function of time delay, defined as

$$u_k^l = \frac{L_k}{\max(L_k)}, \quad k = 1, 2, 3, 4 \tag{15}$$

$$u_k^t = \frac{\min(T_k)}{T_k}, \quad k = 1, 2, 3, 4 \tag{16}$$

Formulas (15) and (16) imply that the relative utility can be improved by increasing the lifetime and decreasing the latency.

TABLE IV

MULTI-HOP SCHEDULING ALGORITHM FOR THE LATENCY OPTIMIZATION OF SERVICE AND SYSTEM

Service and System Latency Optimization based on Multi-Hop Scheduling Algorithm
Input: The optimal multi-hop links $f_{ij}, i\in[1,2,\cdots,N], j\in[0,1,\cdots,N-1]$;
Output: The service latency $T_i, i=1,2,\cdots N$ and the system latency T ;
Step 1: Select the links with $f_{ij}\neq 0$ and the corresponding index i, j ;
Count the number of hops from each sink node $M=\{k_1,\cdots,k_i,\cdots,k_N\}$;
Step 2: Generate the multi-hop links for each sink node to the base station
$R_i=\{r_{i1},\cdots r_{im},\cdots,r_{ik_i} \mid 1\le m\le k_i\}$, $i=1,2,\cdots N$;
r_{im} the $m-th$ multi-hop routing from sink node i to the base station;
$r_{im}=S_i\to\cdots S_{pm}\cdots\to S_{qm}\to BS$, S_{pm} the relay node in the routing;
S_{qm} the last relay node in the routing to the base station;
Step 3: Schedule the links for the first sink node $i=1$
repeat
if $f_{1j}\neq 0,\ j=2,3,\cdots,N+1$ **then**
$h_{1j}=h_{1j-1}+1$, $h_{11}=0$
end if
until all links from the first sink node are scheduled
Step 4: Record the arrival time at sink node j
$T_{aj}=\max h_{ij},\ for\ i=1,2,\cdots N$
Step 5: Schedule the links for other sink nodes
repeat
if $f_{ij}\neq 0,\ i=2,3,\cdots,N,\ j=3,\cdots,N+1$ **then**
for $i=2,3,\cdots,N$
for $j=3,4,\cdots,N+1$
$h_{ij}=T_{aj}+1$
end if
until all links from the other sink nodes are scheduled
Step 6: Calculate the latency for the system
$T=\max h_{ij},\ for\ i=1,2,\cdots N,\ j=2,3,\cdots N+1$
Step 7: Calculate the arrival time at the base station for all links of each sink node, $T_{ai}=\{h^1_{q1N+1},\cdots,h^m_{qmN+1},\cdots,h^{k_i}_{qk_iN+1},\}$, $i=1,2,\cdots N$
Step 8: Calculate the latency for each service
$T_i=\max T_{ri},\ for\ i=1,2,\cdots N$

TABLE V

PARAMETERS OF THE OPTIMIZATION MODEL

Parameter	Describe	Value
E_{ele}	Electric energy	50 nJ/bit
ξ_{fs}	Amplifier energy(d^2)	10 pJ/bit/m^2
ξ_{mp}	Amplifier energy(d^4)	0.0013 pJ/bit/m^4
$E_{initial}$	Initial energy	0.5 J
d (m)	Distance between two adjacent nodes	[20,40,60,100,120,140,160, 180,200]
S (bit)	Data packet size received from sensors layer	[100,200,300,400,500]
N	Number of sink nods	[5,6,7,8,9]
D_T	Lifetime demands	[0.1,0.3,0.5,0.7,0.9]
D_R	Real-time demands	[0.1,0.3,0.5,0.7,0.9]
α	Adaptive weighting factor	0.5
η	The amplification coefficients for the lifetime demands	9
ξ	The amplification coefficients for the real-time demands	0.8
β	The coefficient to adjust the importance of lifetime and latency utility	0.7

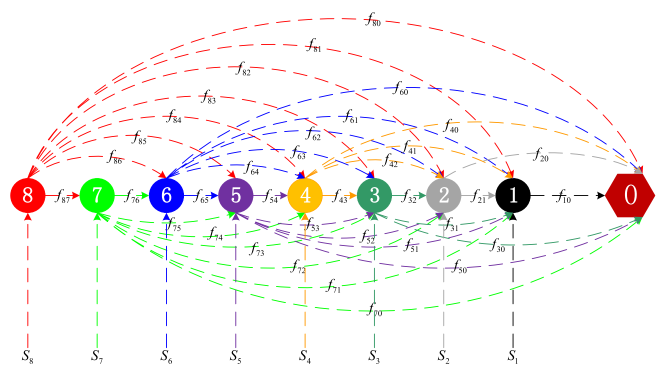

Fig. 5. Optimization Solutions of MTEC, MMEC, MVEC and AUMP Protocols ($N = 8$, $S = 200$ bit, $d = 20$ m).

VI. PERFORMANCE COMPARISON AND VALIDATION

This section validates the performance of the proposed Adaptive Utility Maximization Protocol (denoted as AUMP) in terms of the above four indexes. In addition, the superiority of the AUMP protocol is demonstrated in comparison with the MTEC, MMEC and MVEC protocols.

A. Parameters Configuration

The energy consumption of the sink nodes is based on the multi-path fading model (d^4). The parameters used in simulations are shown in Table V.

It is assumed that there are N sink nodes and one base station deployed linearly and evenly in the railway monitoring field as shown in Fig.3. The distance between any two adjacent sink nodes is d. The size of the data packets collected by the sink nodes from sensor layer is S bit/round. The initial energy of sink nodes is $E_{initial} = 0.5\ J$. In this paper, we take the services with the same importance of lifetime and real-time demands as the simulation objects, such as rail the integrity ($D_T = D_R = 0.5$), rail turnout and expansion rail joint ($D_T = D_R = 0.7$), environment monitoring (wind, temperature) ($D_T = D_R = 0.9$), as shown in Table I. The adaptive model designed in this paper could be applied in different monitoring scenarios with the adjustment of α values. The selection of α is determined by the demands of the monitoring objects.

B. Results and Discussion

The performances of the protocols are evaluated and compared with different parameters using the Lingo software 11.0 and Matlab R2014A (8.3.0.532), which are widely applied in formulating and solving diverse optimization problems. To analyze and discuss the efficiency and adaptability of the proposed protocol, three scenarios are designed to compare the number of hops, latency, lifetime and the relative utility.

Scenario 1: The performances of the four protocols vary with the changing distance among the sink nodes. It is assumed that the number of sink nodes $N = 8$, and the size of data packets is $S = 200$ bit. The distance between two adjacent sink nodes increases from $d = 20$ m to $d = 200$ m. We take one case in Scenario 1 as an example to show the optimization details in this paper. ($N = 8$, $S = 200$ bit, $d = 20$ m).

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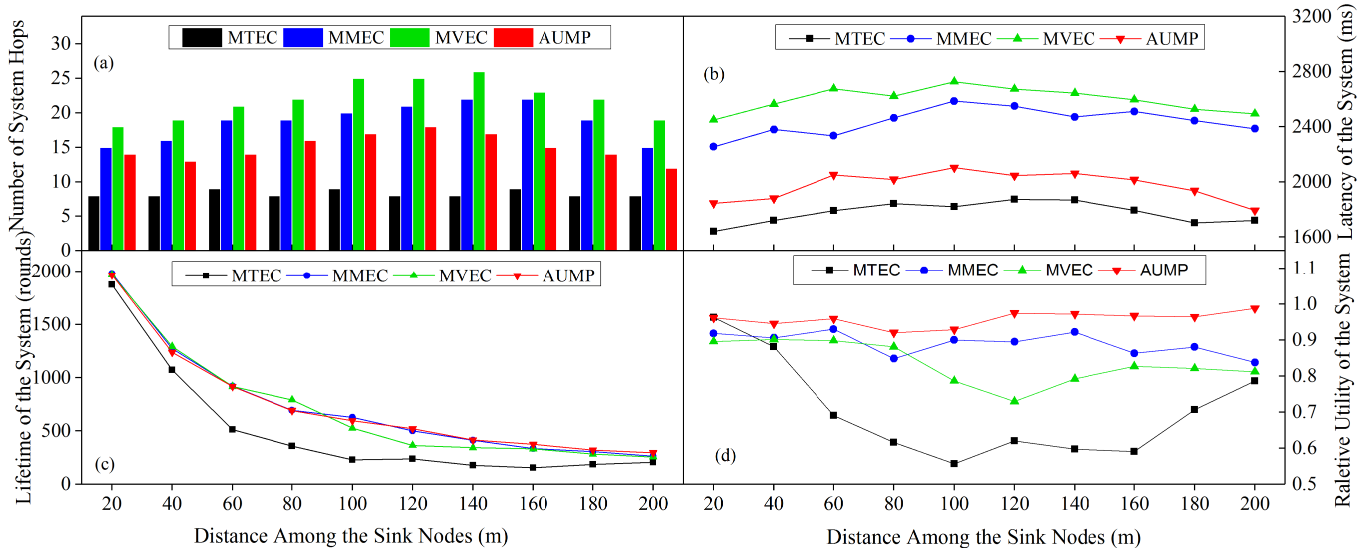

Fig. 6. The Performances of MTEC, MMEC, MVEC and AUMP Protocols for Different Distances among Sink Nodes (Scenario 1). (a) Number of Hops, (b) System Latency, (c) System Lifetime and (d) the System Relative Utility.

TABLE VI

COMMUNICATION LINKS OF THE OPTIMIZATION SOLUTIONS FOR MTEC, MMEC, MVEC AND AUMP PROTOCOLS ($N = 8$, $S = 200$ bit, $d = 20$ m)

	MTEC	MMEC	MVEC	AUMP		MTEC	MMEC	MVEC	AUMP
f_{87}	0	0	13	0	f_{62}	0	0	21	0
f_{86}	0	15	0	34	f_{61}	0	0	42	0
f_{85}	0	15	0	0	f_{60}	200	210	113	224
f_{84}	0	22	0	0	f_{54}	0	10	0	0
f_{83}	0	0	41	0	f_{53}	0	0	0	0
f_{82}	0	0	0	0	f_{52}	0	0	26	107
f_{81}	0	0	0	31	f_{51}	0	0	0	10
f_{80}	200	148	146	135	f_{50}	200	202	202	200
f_{76}	0	0	21	0	f_{43}	0	0	0	0
f_{75}	0	0	0	0	f_{42}	0	21	0	0
f_{74}	0	0	12	0	f_{41}	0	0	0	0
f_{73}	0	0	0	0	f_{40}	200	211	200	211
f_{72}	0	25	0	0	f_{32}	0	0	0	0
f_{71}	0	0	6	0	f_{31}	0	0	0	0
f_{70}	200	183	170	200	f_{30}	200	204	200	206
f_{65}	0	0	23	0	f_{21}	0	50	15	0
f_{64}	0	0	24	0	f_{20}	200	197	185	245
f_{63}	0	0	0	0	f_{10}	200	251	257	203

First, the multi-objective optimization model in Equation (1) is performed, so as to calculate the optimization solution as shown in the matrix (2). The elements in the matrix which represent the links among the sink nodes and the corresponding transmitting data packets size.

The hops number from each sink node could be obtained from the Table:

Second, the energy consumption of each sink nodes is deterministic when the receiving/transmitting packets size and

TABLE VII

HOPS NUMBER OF THE OPTIMIZATION SOLUTIONS FOR MTEC, MMEC, MVEC AND AUMP PROTOCOLS ($N = 8$, $S = 200$ bit, $d = 20$ m)

	MTEC	**MMEC**	**MVEC**	**AUMP**
Hops	8	15	18	14

TABLE VIII

LIFETIME OF THE OPTIMIZATION SOLUTIONS FOR MTEC, MMEC, MVEC AND AUMP PROTOCOLS ($N = 8$, $S = 200$ bit, $d = 20$ m)

	MTEC	**MMEC**	**MVEC**	**AUMP**
Maximum Energy Consumption (mJ)	26.66	25.23	25.39	25.43
System Lifetime (round)	1875	1981	1969	1966

the communication routing are all determined, and the lifetime of the sink nodes and the system could be calculated. The initial energy of each sink node is 0.5J. The maximum energy consumption of all the sink nodes in one round is calculated by the energy consumption model in Equations (4)-(6), and the system lifetime is calculated by Equation (13).

Third, the algorithm in Table III is carried out to calculate the latency of each sink node and the system. The order of the hops for all sink nodes are optimized to reduce the transmission phases from the original nodes to the base station. The time consumption in each phase is 205ms, and the system latency is calculated correspondingly.

Forth, the relative lifetime and latency utilities are calculated based on Equations (15) and (16), and then the relative system utility is calculated by Equation (14).

Fig.6 shows the performances of the MTEC, MMEC, MVEC and AUMP. Fig. 6(a) indicates that the hops of the METC are almost constant with varying distance. However, the hops of the other three protocols increase first and then

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TABLE IX
LATENCY OF THE OPTIMIZATION SOLUTIONS FOR MTEC, MMEC, MVEC AND AUMP PROTOCOLS ($N = 8$, $S = 200$ bit, $d = 20$ m)

	MTEC	MMEC	MVEC	AUMP
Communication Phases	8	11	12	9
System Latency (ms)	1640	2255	2460	1845

TABLE X
UTILITY OF THE OPTIMIZATION SOLUTIONS FOR MTEC, MMEC, MVEC AND AUMP PROTOCOLS ($N = 8$, $S = 200$ bit, $d = 20$ m)

	MTEC	MMEC	MVEC	AUMP
Latency Utility	1	0.73	0.67	0.89
Lifetime Utility	0.95	1	0.99	0.99
System Utility	0.96	0.92	0.89	0.96

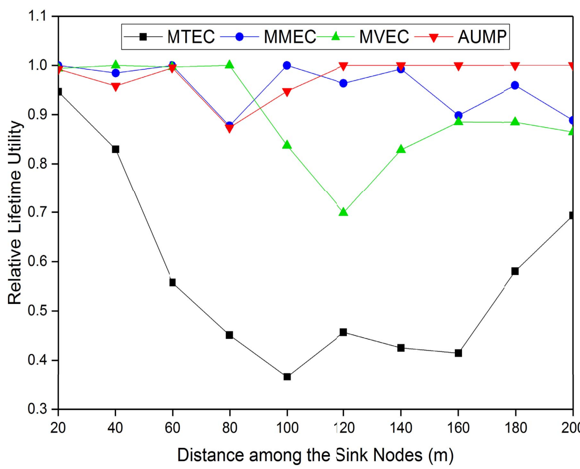

Fig. 7. Relative Lifetime Utility of MTEC, MMEC, MVEC and AUMP Protocols for Different Distances among Sink Nodes (Scenario 1).

drop with increasing distance, while the hops of AUMP get the peak when $h = 17$ at $d = 120$ m. This trend reveals that the gap of the energy consumption can be narrowed by fewer hops when the nodes are close to each other. When the distance is too large, it is hard to balance the energy consumption by increasing the hops, and then the system will communicate with fewer hops to decline the system latency. The number of hops based on AUMP is larger than MTEC but less than MMEC and MVEC. The MVEC has the most hops because of the ultimate pursuit for the balance. Fig. 6(b) shows the similar trend, whereas there is no consistent one-to-one match between the hops and latency. Some hops performed at the same time with the scheduling optimization strategy, and it is helpful to reduce the latency. Fig. 6(c) illustrates that the lifetime of the AUMP is close to MMEC and MVEC, owing to the re-optimization scheme based on the residual energy, while latency is larger than MTEC which ignores the balance of energy consumption. However, with increasing distance, the unbalance degree of energy consumption for all the protocols is close to each other and the lifetime is getting closer

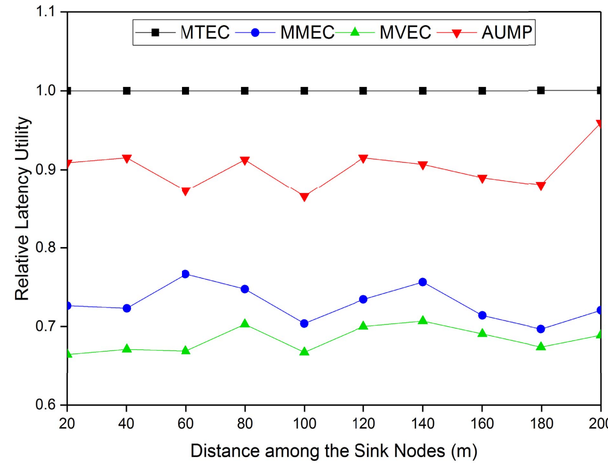

Fig. 8. Relative Latency Utility of MTEC, MMEC, MVEC and AUMP Protocols for Different Distances among Sink Nodes (Scenario 1).

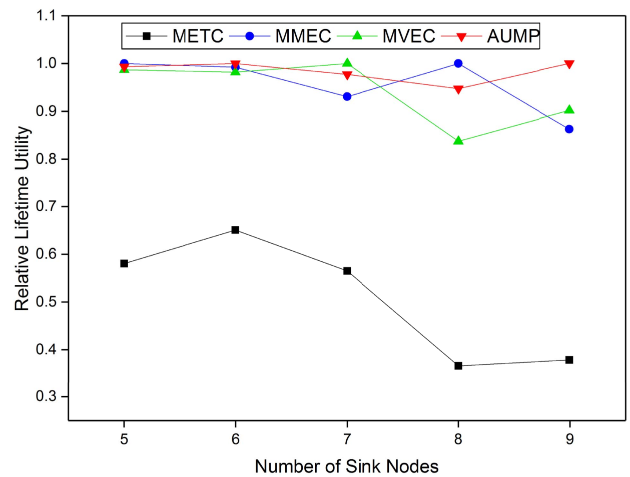

Fig. 9. Relative Lifetime Utility of MTEC, MMEC, MVEC and AUMP Protocols for Different Distances among Sink Nodes (Scenario 2).

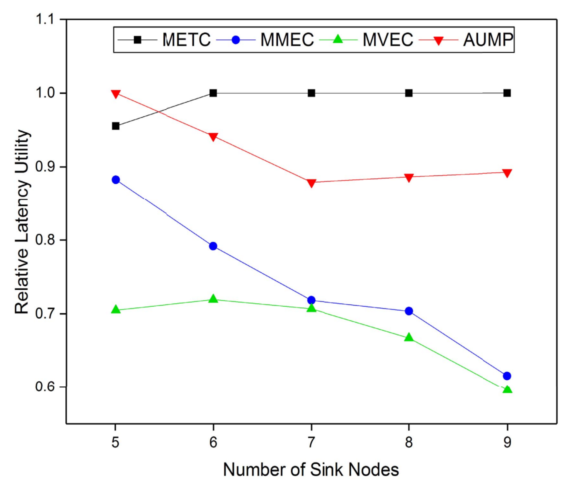

Fig. 10. Relative Latency Utility of MTEC, MMEC, MVEC and AUMP Protocols for Different Distances among Sink Nodes (Scenario 2).

as well. The relative utilities of all the protocols are shown in Fig. 6(d) and Table IV. Obviously, the utility of AUMP is larger than those of the other three protocols. Because of the

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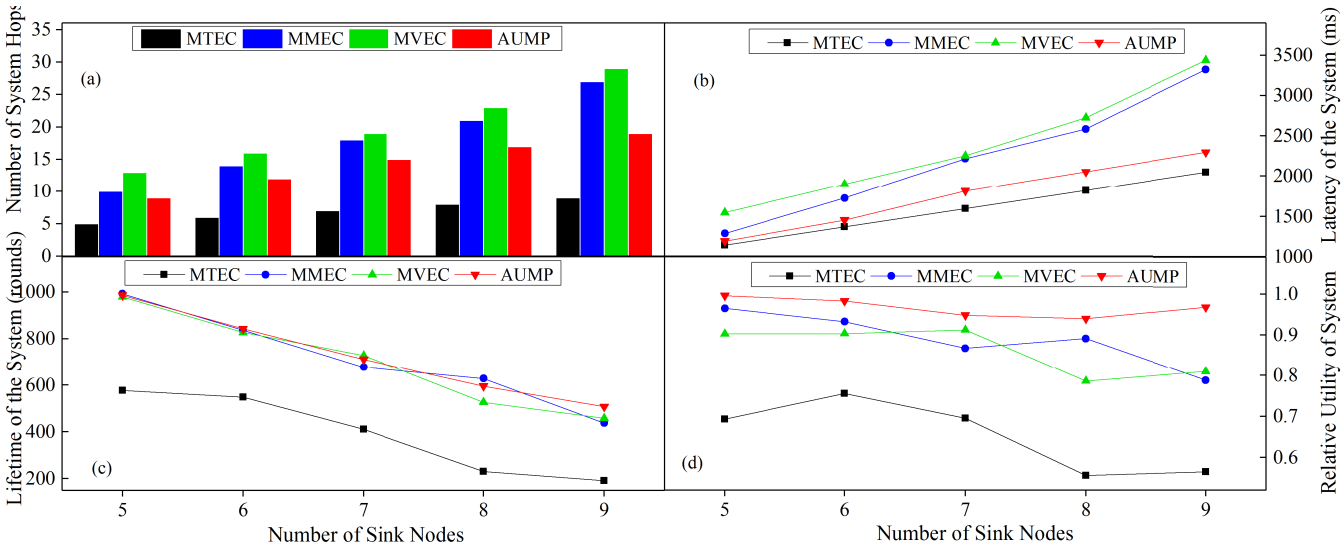

Fig. 11. The Performances of MTEC, MMEC, MVEC and AUMP Protocols for Different Number of Sink Nodes (Scenario 2).(a) Number of Hops, (b) System Latency, (c) System Lifetime and (d) the System Relative Utility.

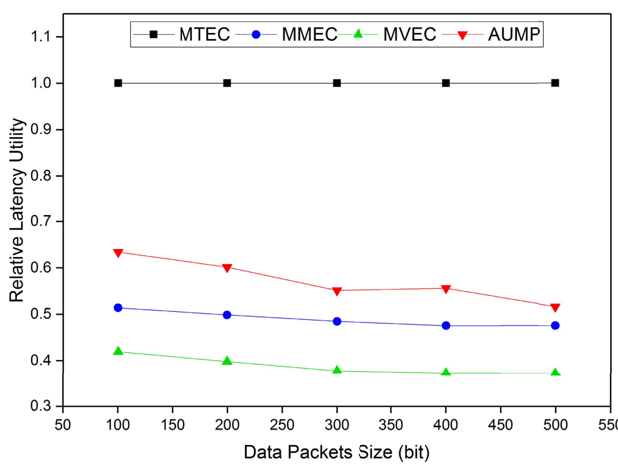

Fig. 12. Relative Lifetime Utility of MTEC, MMEC, MVEC and AUMP Protocols for Different Distances among Sink Nodes (Scenario 3).

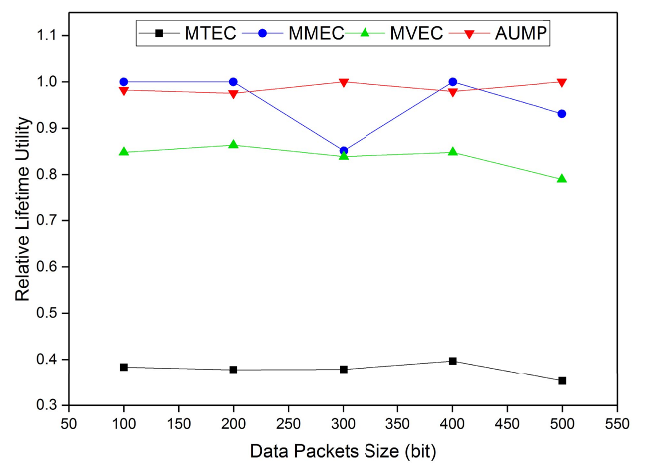

Fig. 13. Relative Latency Utility of MTEC, MMEC, MVEC and AUMP Protocols for Different Distances among Sink Nodes (Scenario 3).

nearly same lifetime at $d = 200$ m, the utility of MTEC is close to MVEC and MMEC while still less than AUMP. Because the primary task of the monitoring system is to gather the service condition information, the lifetime has a bigger impact on the system utility compared with the latency as shown in Fig.7 and Fig.8.

Scenario 2: The performance of the four protocols varies with the number of sink nodes. It is assumed that the distance between two adjacent nodes is $d = 100$ m, and the size of data packets is $S = 200$ bit.

Fig 11 shows the performance of the MTEC, MMEC, MVEC and AUMP with the number of the sink nodes increasing from $N = 5$ to $N = 9$. Fig. 11(a) exhibits that the hops of the MTEC, MMEC, MVEC and AUMP are increasing as the number of sink nodes increases. The column graph implies that the gap of the energy consumption is growing with the similar trend. However, the sink nodes that can be selected as the relay nodes to balance the energy consumption by multi-hops. The corresponding relationship between the increasing hops and extending latency is reflected in Fig. 11(b), although this is not a significant positive correlation. The latency of AUMP is close to MTEC while much less than MMEC and MVEC, which is benefited from fewer hops and more reasonable scheduling scheme. The varying lifetime is displayed in Fig. 11(c), which shows that the lifetime of MTEC is much less than those of the other three protocols and decreases gradually with the sink nodes number increasing. The lifetime of AUMP keeps slightly ahead compared with MMEC and MVEC and declines approximately linearly with the sink nodes increasing. The relative utility of AUMP is obviously superior to those of the other three protocols, as shown in Fig. 11(d) and Table XI. The lifetimes of MMEC and MVEC change the leading position with varying sink nodes, and the utilities change with the similar trend. The lifetime and latency utilities of the four protocols as the number of sink nodes varies are displayed in Fig.9 and Fig.10.

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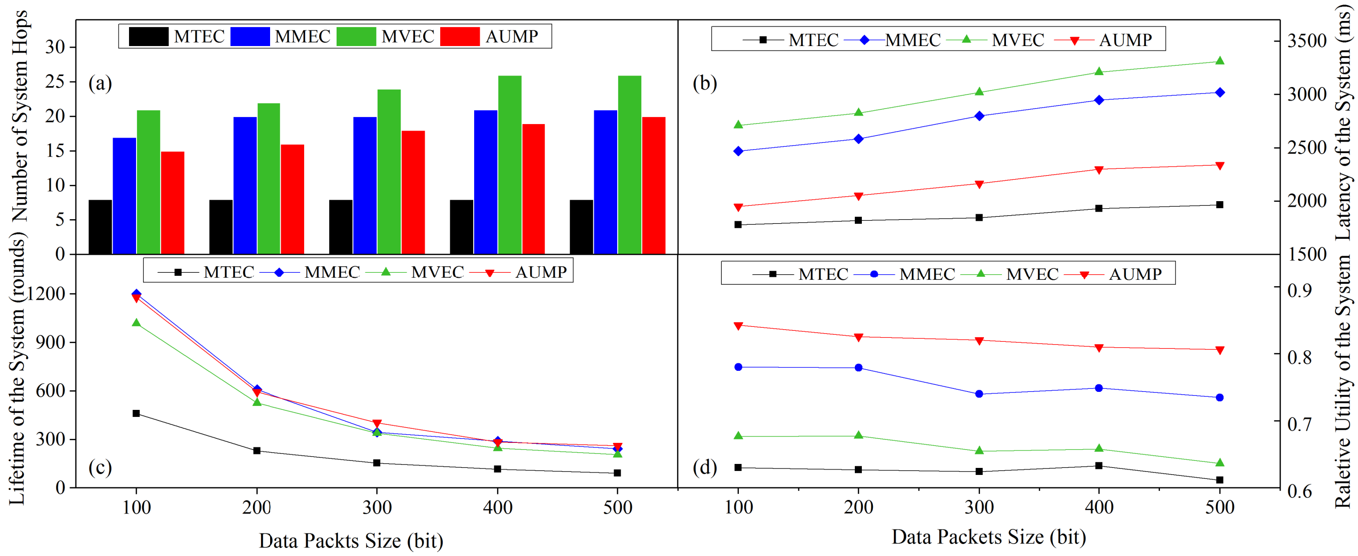

Fig. 14. The Performances of MTEC, MMEC, MVEC and AUMP Protocols for Different Data Packet Sizes (Scenario 3). (a) Number of Hops, (b) System Latency, (c) System Lifetime and (d) the System Relative Utility.

TABLE XI
RELATIVE UTILITIES IN DIFFERENT SCENARIOS

	Distance(m)	**d=40**	**d=80**	**d=120**	**d=160**	**d=200**
Scenario 1:	**MTEC**	0.881	0.616	0.620	0.590	0.786
	MMEC	0.906	0.848	0.895	0.863	0.838
	MVEC	0.901	0.881	0.729	0.827	0.812
	AUMP	0.945	0.920	0.975	0.967	0.988
	Number	**N=5**	**N=6**	**N=7**	**N=8**	**N=9**
Scenario 2:	**MTEC**	0.693	0.756	0.696	0.556	0.565
	MMEC	0.965	0.932	0.867	0.891	0.788
	MVEC	0.902	0.903	0.912	0.787	0.810
	AUMP	0.995	0.983	0.948	0.939	0.968
	Size(bit)	**S=100**	**S=200**	**S=300**	**S=400**	**S=500**
Scenario 3:	**MTEC**	0.630	0.627	0.624	0.633	0.611
	MMEC	0.781	0.779	0.740	0.749	0.735
	MVEC	0.677	0.677	0.655	0.658	0.636
	AUMP	0.843	0.826	0.821	0.810	0.807

Scenario 3: In this case, we show the performance of the four protocols vary with increasing data packets size. It is assumed that the number of sink nodes is $N = 8$, and the distance between two adjacent nodes is $d = 100$ m.

Fig 14 shows the performances of the MTEC, MMEC, MVEC and AUMP as the size of data packets received from the sensor layer for each sink nodes varies from $S = 100$ bit to $S = 500$ bit. Figs. 14(a) and 14(b) show that both of the number of hops and the latency of AUMP are smaller than those of MMEC and MVEC while larger than those of MTEC. Meanwhile, both the hops and latency increase gradually, and this implies that the effect of the data size on the multi-hop communication structure is limited and the data packets size ineach hop will grow with the received data packets increasing. However, the lifetime of the system declines sharply as shown in Fig. 14(c), because the energy consumption of the sink nodes is related to the transmitted data packets size. Note that the MVEC focuses more on balancing the energy consumption, and this leads to unnecessary energy consumption. Thus, the lifetime of MVEC is shorter than those of MMEC and AUMP but longer than that of MTEC. As shown in Fig. 14(d) and Table XI, the utility of AUMP is higher than those of the other three protocols. Because of the high latency and low lifetime, the utility of MVEC is close to MTEC but much less than MMEC and AUMP. Due to the similar changing trend in latency and lifetime, the utility of AUMP varies smoothly as the data packets size increases as shown in Fig.12 and Fig.13.

Finally, the simulation results and discussions can be summarized as follows.

- The relative utility of AUMP is superior to those of the other three protocols. It keeps stable in any scenario, especially with the varying distances in Scenario 1, whereas the other protocols' utilities vibrate obviously.
- The number of hops and latency of AUMP are similar to those of MTEC while much smaller than those of MMEC and MVEC. However, its lifetime is close to those of MMEC and MVEC, but much longer than that of MTEC. Railway monitoring systems have a critical requirement on lifetime and real-time characteristics, and thus AUMP is a preferable protocol.
- The system latency can be reduced using the multi-hops scheduling optimization strategy. The multi-hops scheduling methodology could be used to improve the utility of the system via decreasing the latency and enhancing the lifetime simultaneously.
- The single-objective optimization and single-indicator evaluation are not effective for practical application, particularly for complex railway monitoring systems. Comparatively, the multi-objective optimization and the comprehensive evaluation utility show to be more effective.

- The classification for the requirements of each service in the railway monitoring system could be used to guide the design of the adaptive weighting factor and varying structure of the optimization model adaptively.

VII. Conclusion

This paper proposes an adaptive multi-objective optimization model for the multi-hop communication protocol. By optimizing the multi-hop routing plan and the corresponding hops, latency, and lifetime, the comprehensive performance of the proposed methodology distinguish itself from most existing approaches with the following contributions.

First, the multi-objective optimization model is proposed to minimize and balance the energy consumption, which helps decrease the system latency and increase the lifetime simultaneously.

Second, the scheduling optimization strategy is applied to manage the order of all hops, which could obtain a further latency reduction.

Finally, the model is verified by case studies in different scenarios. Results show that the number of hops and latency of AUMP are similar to those of MTEC while much smaller than those of MMEC and MVEC. However, the lifetime of AUMP is close to those of MMEC and MVEC while much longer than that of MTEC. Whereas in view of the comprehensive performance of the system, the relative system utility of AUMP proposed in this paper is obviously superior to those of many other protocols.

VIII. Future Work

This paper focuses on the lifetime and latency optimization for the high-speed railway wireless monitoring system, and the optimization model is designed based on the monitoring objects and the corresponding data characteristics. The simulation results show the effectiveness of the proposed algorithm in the comprehensive performance improvement.

It should be noted that the optimization model is not restricted to the high speed railway wireless monitoring system. It can also be used in other wireless monitoring system with the similar linear wireless monitoring and communication structure, but the optimization approach should be adjusted correspondingly. We will study the data characteristics in other filed in the future, and try to design a universal model for the sort of problems in ordinary railway operations, motorways or other traffic modes, so as to improve the availability of the wireless monitoring system in intelligent transportation systems.

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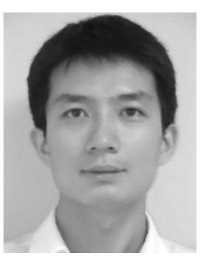

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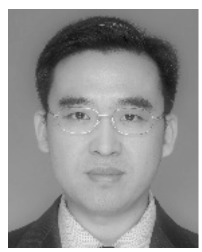

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