Stream Data Gathering in Wireless Sensor Networks within Expected Lifetime

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ABSTRACT
Sensor networks aim at collecting important sensor data for environment monitoring, e-health or hazardous conditions. Some applications do not need sensor networks with a long lifetime, such as monitoring an erupting volcano or monitoring hazardous conditions. These applications generally expect that sensor networks have reliable performance and provide continuous data streams during a short expected lifetime. In this work, we investigate the stream data gathering problem in sensor networks within an expected lifetime. Two important problems for stream data gathering are: 1) maximizing stream data gathering in wireless sensor networks within an expected lifetime; 2) minimizing transmission delay for stream data gathering in wireless sensor networks within an expected lifetime. The Maximum Stream Data Gathering (MSDG) algorithm and the Minimum Transmission Delay (MTD) algorithm are proposed to solve these two problems. Simulation results show that our algorithms can essentially solve the identified problems.

Keywords
Stream data gathering, sensor network, expected lifetime

1. INTRODUCTION
Wireless sensor networks have received tremendous interest from current computer research community in recent years. A wireless sensor network usually consists of a large number of small, inexpensive sensor nodes, which are collectively able to form a network. Wireless sensor networks have been used in a large amount of applications in both scientific and military fields [1]. Sensor nodes can be densely deployed to monitor the environment and collect useful information on their surroundings. Collected information is often encoded as stream data and transmitted to a base station for further analysis. Generally, individual sensor node produces non-stream data. However, several sensor nodes may send their data to one cluster head simultaneously, which easily results in stream data transmission in cluster head level. Furthermore, in some applications when image sensor node and audio sensor node even video sensor node are used in sensor networks multimedia stream data can easily appear. Wireless sensor networks are usually battery powered. How to use battery powered sensor networks to achieve a long lifetime is currently a critical research issue. Many research works had been done to prolong the lifetime of sensor networks in different aspects, such as maximizing lifetime routing [2] and maximizing lifetime data gathering [10, 13, 16]. Some other research approaches this problem in a different manners, such as minimizing energy consumption for routing [3] and minimizing energy consumption for data gathering [14, 15]. However, some applications do not require sensor networks to operate for long periods of time, such as monitoring erupting volcanoes [4] or monitoring conditions in a battlefield [5] for several hours. These applications generally expect that sensor networks can deliver stream data as much as possible by operating continuously during a relatively short expected lifetime without sleeping. Considering these applications as our motivation, we study the following problems: 1) how to maximize stream data gathering in wireless sensor networks within an expected lifetime; and 2) how to minimize transmission delay for stream data gathering in wireless sensor networks within an expected lifetime. In this paper, we investigate both problems in sensor networks within an expected lifetime. We propose two algorithms: 1) the MSDG (Maximum Stream Data Gathering) algorithm and 2) the MTD (Minimum Transmission Delay) algorithm to solve our identified problems respectively. The experimental results show that the physically allowed maximum transmission radius of sensor nodes and expected lifetime are the two major factors that can affect the result of stream data gathering and transmission delay.

The rest of this paper is organized as follows. We present a short survey about related work in section 2. In section 3, we present the used radio energy model in this paper. In section 4, we present the problem statement. In section 5, we present the condition how the expected lifetime can be guaranteed. We describe the used routing scheme in this paper in section 6. We discuss the maximizing stream data gathering problem and minimizing transmission delay in section 7 and 8 respectively. We present the simulation results in section 9 and conclude in section 10. [1]

2. RELATED WORK
The problem of data gathering in wireless sensor networks has been investigated by many researchers in different aspects. Basically, we can classify them into three different categories: 1) maximizing lifetime of sensor networks; 2) balancing data gathering in sensor networks; 3) maximizing data gathering in sensor networks. In this section we review the related work in each category.

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Maximizing lifetime of sensor networks – The LEACH protocol [6] presents a solution for this data gathering problem, where a small number of clusters are formed in a self-organized manner. A designated node in each cluster as the cluster head collects and fuses data from other nodes in its cluster and transmits the result to the base station. The key idea in LEACH is to reduce the number of nodes communicating directly with the base station by forming randomized clusters. However, the main drawback of this protocol is that it requires all nodes must be able to directly communicate with the base station. In PEGASIS [7], sensor nodes are arranged into chains so that each sensor node transmits and receives from a nearby neighbor node. Gathered data is transferred from node to node, aggregated and eventually transmitted to the base station. In [8], a hierarchical scheme based on PEGASIS is proposed for reducing the average energy and delay incurred in gathering the sensed data. In [9], authors consider the problem of placing nodes in the monitoring area and assigning roles to them such that the system lifetime is maximized, while ensuring that each region of interest is covered by at least one sensor node. This is the maximum lifetime sensor deployment problem with coverage constraints. In [10], data gathering is assumed to be 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 [11], authors study the problem by proposing another protocol called PEDAP, which uses heuristics to assign weights to links and finds a minimum spanning tree rooted at the base station in terms of total transmission energy consumption. In [12], authors study data gathering problem in a cluster-based sensor network. During data gathering, sensors have the ability to perform in-network aggregation (fusion) of data packets and route to the base station while maximizing the system lifetime given the energy constraints. In [13], authors focus on data gathering problems in energy-constrained networked sensor systems, proposing optimal algorithms based on network flows and heuristics based on self-stabilizing spanning trees and shortest paths.

Balancing data gathering in sensor networks – In [17, 18], the balanced data transfer problem is formulated as a linear programming problem where a *minimum achieved sense 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 a requirement of sufficient coverage for all the sensor locations surveyed. The authors outline an algorithm for finding approximately optimal placements for the relay nodes, given a system of basic sensor locations and compare it with a straightforward grid arrangement of the relays.

Maximizing data gathering in sensor networks – In [19], the data gathering problem is formulated as a linear programming problem and a 1+ω approximation algorithm is proposed. This algorithm further leads to a distributed heuristic. In [20], a nonlinear programming formulation is proposed to explore the trade-offs between energy consumed and the transmission rate in sensor networks. It models the radio transmission energy according to Shannon's theorem. In [21], authors aim at maximizing the throughput of data received by the base station. By modeling the energy consumption associated with each send and receive operation, the authors formulate the data gathering problem as a constrained network flow optimization problem. The authors develop a decentralized and adaptive algorithm for the maximum network flow problem. This algorithm is a modified version of the Push-Relabel algorithm [22].

Through above survey work, to our best knowledge, we find that there is no any research work that had ever considered taking expected lifetime of a sensor network as an important parameter for steam data gathering in wireless sensor networks. This area is the focus of this paper.

3. RADIO ENERGY MODEL

Our energy model for sensors is based on the first order radio model described in [6]. In this model, the radio dissipates E_{elec} to power the transmitter or receiver circuitry, and E_{amp} for the transmit amplifier. The energy expended to transmit a *k*-bit message to a distance *d* is:

$$ETx(k, d) = E_{elec} * k + E_{amp} * k * d^r, \ (r = 2 \text{ or } 4) \quad (1)$$

while the energy expended to receive this message is

$$ERx(k) = E_{elec} * k, \quad (2)$$

which is a constant for a fixed-size message. We consider the transmission radius of sensor node *TR* as the distance *d.*

4. PROBLEM STATEMENT

We consider a wireless sensor network consisting of *N* sensor nodes and a base station which are randomly distributed over an interested region. The locations of sensor nodes and base station are fixed. The base station has the knowledge of the locations of all sensor nodes, which can be obtained by using GPS. Each sensor node has transmission radius *TR* and *M* neighbor sensor nodes within *TR*. Sensor nodes can dynamically adjust the transmission radius. Among *N* sensor nodes *C* sensor nodes work as source nodes. All source nodes continuously produce sensed data with a minimum data generation rate *R* Kbps. Source nodes can dynamically increase data generation rate. The data from source nodes are gathered and sent to base station for further processing. Our problems are: 1) letting base station gathering as much sensed data as possible within an expected lifetime; 2) letting data transmission as fast as possible in sensor network within an expected lifetime.

5. GUARANTEE EXPECTED LIFETIME

Initial energy of sensor node is *ESN*. The initial total energy of whole sensor network is fixed as *N* * *ESN*. The real lifetime of sensor network is *LT*. The expected lifetime of sensor network is *ELT*. The key factor for determining the lifetime of a sensor network is the way that this sensor network consumes its energy. The real energy consumption rate of a sensor network *ECR(SN)* can be defined as

$$ECR(SN) = N * ESN / LT. \quad (3)$$

The expected energy consumption rate *ECR(ESN)* can be defined as

$$ECR(ESN) = N * ESN / ELT. \quad (4)$$

In order to guarantee the expected lifetime of a sensor network, the real lifetime of a sensor network must no smaller than the expected lifetime

$$LT \geq ELT, \quad (5)$$

which implies that the real energy consumption rate must not be larger than the expected energy consumption rate

$$ECR(SN) \leq ECR(ESN), \quad (6)$$

which also means that any sensor node's energy consumption rate should not be larger than one N^{th} expected energy consumption rate of the whole sensor network

$$ESN / LT \leq ESN / ELT. \quad (7)$$

For end-to-end stream data transmission, any sensor node within a transmission path has the energy consumption rate *ECR(node)*

$$ECR(node) = R * (2 * E_{elec} + E_{amp} * TR^{r}). \quad (8)$$

Thus, to guarantee the expected lifetime, we must find suitable *R* and *TR* to satisfy following equation (9)

$$R * (2 * E_{elec} + E_{amp} * TR^{r}) \leq ESN / ELT. \quad (9)$$

6. ROUTING SCHEME

In this paper we use geographical greedy forwarding [23] as our routing scheme. In a geographical greedy forwarding scheme, source nodes know the location of the base station. Produced data is forwarded to one of its 1-hop neighbor node which is closest to the base station among all neighbor nodes. This process is repeated until the data reaches the base station. Geographical greedy forwarding suffers from the routing holes problem [23]. For example, data can be blocked at a node who has no any 1-hop neighbor node is in the transmission radius. However, in this paper we do not discuss this issue since it had been solved by [23].

7. MAXIMUM DATA GATHERING

Within expected lifetime *ELT*, a base station can receive the total data *D* from *C* source nodes as:

$$D = C * R * ELT. \ (R \leq TC) \quad (10)$$

Since both *C* and *ELT* are fixed parameters, to maximize the *D* means to maximize *R*. Therefore, we should explore in what kind of situation the *R* can be increased. *TC* is the sensor nodes' maximum transmission capacity.

7.1 Minimum Energy for Multi-hop Routing

When source nodes transmit stream data to a base station with minimum generation rate *R* by using the geographical greedy forwarding algorithm, a general problem can be formulated as following: given a distance d_{sbi} between a source node S_i and the base station, to find the optimal *TR* so that the total energy used for multi-hop routing can be minimized. The transmission hop *Ki* is equal to:

$$Ki = d_{sbi} / TR. \quad (11)$$

Thus, the total consumed energy *E* for multi-hop routing in one second can be formulized as:

$$E = d_{sbi} / TR * R * (2 * E_{elec} + E_{amp} * TR^{r}). \quad (12)$$

Mathematically, it is a convex optimization problem. The optimal transmission radius *OTR* can be found as:

$$OTR = (2 * E_{elec} / E_{amp})^{1/r}. \quad (13)$$

7.2 Energy Consumption Rate

Sensor nodes are physically allowed to use maximum transmission radius *MTR* to transmit data, thus the energy consumption rate *ECR(MTR)* of sensor nodes when they are using *MTR* can be formulized as:

$$ECR(MTR) = R * (2 * E_{elec} + E_{amp} * MTR^{r}). \quad (14)$$

When sensor nodes use the *OTR* to transmit stream data, the energy consumption rate *ECR(OTR)* can be formulized as:

$$ECR(OTR) = R * (2 * E_{elec} + E_{amp} * OTR^{r}). \quad (15)$$

When sensor nodes consume the energy same as the expected energy consumption rate, we can easily calculate the allowed transmission radius *ETR* as:

$$ETR = ((ESN / (ELT * R) - 2 * E_{elec}) / E_{amp})^{1/r}. \quad (16)$$

Thus, the energy consumption rate of sensor nodes when using *ETR* to transmit stream data can be formulized as:

$$ECR(ETR) = R * (2 * E_{elec} + E_{amp} * ETR^{r}).. \quad (17)$$

7.3 Choosing Transmission Radius

Different transmission radius should be used in different conditions. By analyzing three different energy consumption rates, we can propose the following criteria to choose the appropriate transmission radius for stream data transmission.

- If *ECR(ETR)* < *ECR(MTR)* < *ECR(OTR)*, then choose *ETR* for stream data transmission.
- If *ECR(ETR)* < *ECR(OTR)* < *ECR(MTR)*, then choose *ETR* for stream data transmission.
- If *ECR(MTR)* < *ECR(ETR)* < *ECR(OTR)*, then choose *MTR* for stream data transmission.
- If *ECR(MTR)* < *ECR(OTR)* < *ECR(ETR)*, then choose *MTR* for stream data transmission.
- If *ECR(OTR)* < *ECR(MTR)* < *ECR(ETR)*, then choose *OTR* for stream data transmission.
- If *ECR(OTR)* < *ECR(ETR)* < *ECR(MTR)*, then choose *OTR* for stream data transmission.

When sensor nodes use *ETR* for stream data transmission there is no more space for source nodes to increase the *R*. However, when sensor nodes use *MTR* or *OTR* for stream data transmission, there are still some space for source nodes to increase the *R*. The maximum *R* can be formulized as follows:

$$R_{MAX\_MTR} = ECR(ETR) / (2 * E_{elec} + E_{amp} * MTR^{r}). \quad (18)$$

$$R_{MAX\_OTR} = ECR(ETR) / (2 * E_{elec} + E_{amp} * OTR^{r}). \quad (19)$$

Thus, the maximum stream data gathering can be calculated using:

$$D = C * R_{MAX} * ELT. \ (R_{MAX} \leq TC) \quad (20)$$

7.4 Proposed MSDG Algorithm

Based on our previous analysis, we propose the Maximum Stream Data Gathering (MSDG) algorithm to maximize stream data gathering in wireless sensor networks within an expected lifetime.

- *Initialize: ELT*
- *Step 1: Calculate ECR(MTR), ECR(OTR), ECR(ETR) based on equations (14), (15), (17);;*
- *Step 2: Choose the appropriate transmission radius for stream data transmission based on criteria presented in subsection 7.3;*
- *Step 3: Calculate the maximum* R_{MAX} *based on equations (18) or (19);*

- *Step 4: Use chosen TR and calculated R_{MAX} to transmit stream data to base station.*

7.5 Multi-path Transmission

Multi-path transmission [24] is used to increase transmission performance in wireless sensor networks. When R > TC, we use multiple transmission path to transmit stream data to base station. Thus, the received stream data can be defined as:

$$D = C * R * ELT. \quad (R > TC). \qquad \textbf{(21)}$$

The number of path is decided by the R. For example, If $TC < R \leq 2 * TC$, then number of the transmission should be 2; If $2* TC < R \leq 3 * TC$, then number of the transmission should be 3.

8. Minimum Transmission Delay

Transmission delay actually is contributed by the number of hops. The problem for minimizing transmission delay can be formulated as following: given a distance d_{sbi} between a source node S_i and the base station, to find the maximum TR so that the total number of hops used for multi-hop routing can be minimized.

8.1 Choosing Transmission Radius

Based on subsection 7.2 we have energy consumption rates *ECR(MTR)* and *ECR(ETR)*. We propose following criteria to choose the larger transmission radius to minimize the number of hop used for multi-hop routing.

- If *ECR(ETR)* < *ECR(MTR)*, then choose *ETR* for stream data transmission.
- If *ECR(MTR)* < *ECR(ETR)*, then choose *MTR* for stream data transmission.

When sensor nodes use *MTR* for stream data transmission, we can still use source node to increase the *R* to maximize the stream data gathering as equation (18).

8.2 Proposed MTD Algorithm

Based on forgoing analysis, we propose the Minimum Transmission Delay (MTD) algorithm to minimize transmission delay for stream data gathering in wireless sensor networks within an expected lifetime.

- *Initialize: ELT*
- *Step 1: Calculate ECR(MTR), ECR(OTR) based on equations (14), (17);*
- *Step 2: Choose the larger transmission radius for stream data transmission based on criteria presented in subsection 8.1;*
- *Step 3.1:If ECR(MTR) < ECR(ETR), calculate the maximum R_{MAX} based on equation (18) then use chosen TR and calculated R_{MAX} to transmit stream data to base station;*
- *Step 3.2: If ECR(ETR) < ECR(MTR), then use ETR and minimum R to transmit stream data to base station.*

9. SIMULATION

9.1 Simulation Environment

In order to evaluate our proposed algorithms and to see the changed network topology based on different expected lifetime, we have implemented a sensor network simulator called NetTopo [25]. NetTopo allow users to deploy a sensor network with a size up to 500 M * 500 M, number of sensor node up to 400, and number of source nodes up to 99. Table 1 shows the parameters used in our simulation.

Table 1. Simulation parameters

Parameter	**Value**
Network Size	500 M * 500 M
Base Station Location	Corner or Central
Number of Base Station	1
Number of Sensor Node	390
Number of Source Node	16
Initial Energy of Base Station	Not limited
Initial Energy of Sensor Node	36 J (3 batteries)
Minimum Flux of Stream Data *R*	5 kbps
Sensor Node Maximum *TC*	20 kbps
Radio Model	The first order radio model
Maximum TR *MTR*	Not fixed
E_{elec}	50 nj/bit
E_{amp}	0.1 nj/bit/m^2
Optimal TR *OTR*	100 M

9.2 Evaluation of MSDG Algorithm

The physical allowed transmission radius *MTR* is an important parameter that can affect the amount of the received stream data in base station. In our simulation we set *MTR* = 70 M, 80 M, 90M, 110M and 120M respectively. From simulation results as shown in Figures 1, 2 and 3, we can see that a shorter *MTR* allows more stream data gathering but also needs more relay nodes to participate in every routing path, and the corresponding average

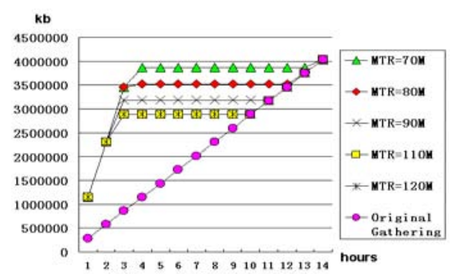

Figure 1. Stream data gathering vs. expected lifetime

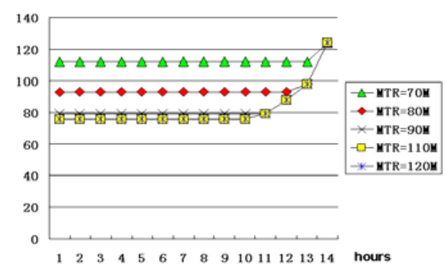

Figure 2. Total number of relay node vs. expected lifetime

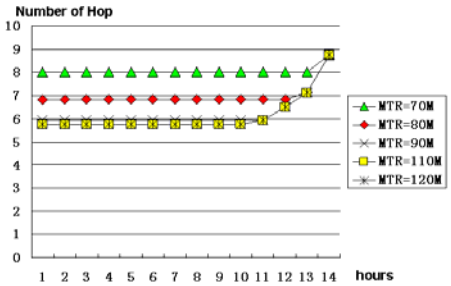

Figure 3. Average delay vs. expected lifetime

delay is also longer. When *MTR* ≥ *OTR*, sensor nodes only use *OTR* for stream data transmission, the maximum amounts of stream data gathering in conditions when *MTR* = 110M and *MTR* = 120M are same. The line of *Original Gathering* in Figure 1 shows the gathered stream data without using MSDG algorithm. It can be seen from Figure 1 that the MSDG algorithm maximizes the stream data gathering given a fixed *MTR* within a fixed expected lifetime. For example, given *MTR* = 110M, by using MSDG algorithm, sensor nodes can maximize the stream data gathering within an expected lifetime set to 10 hours. When expected lifetime increases to 14 hours, sensor nodes have to use the expected transmission radius to transmit stream data in any situation. Thus, these five lines in Figure 1 finally converged at the same point.

9.3 Evaluation of MTD Algorithm

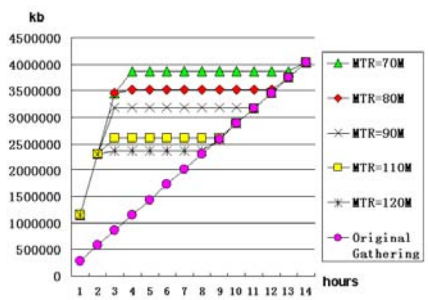

Figure 4. Stream data gathering vs. expected lifetime

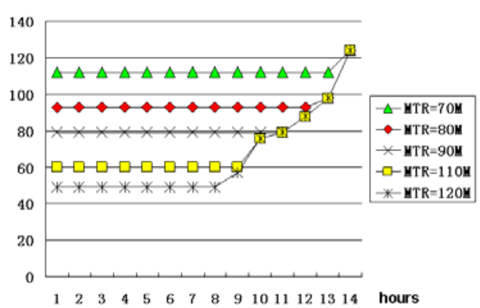

Figure 5. Total number of relay node vs. expected lifetime

From our simulation results as shown in Figures 4, 5, and 6, we can see that a shorter *MTR* leads to longer average transmission delay, and longer expected lifetime also leads to a longer average

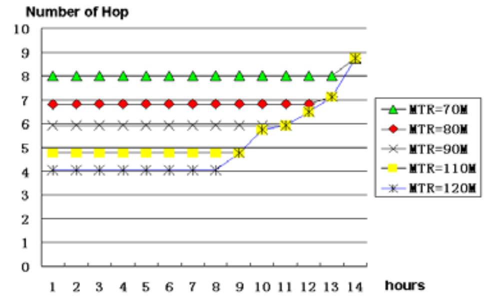

Figure 6. Average delay vs. expected lifetime

transmission delay. When sensor nodes use MTD algorithm to transmit stream data, the results of maximum stream data gathering are different from those shown in figure 3 because in MTD algorithm the *MTR* is used instead of *OTR*. However, MTD algorithm can essentially reduce the transmission delay. For example, given *MTR* = 120M, MTD algorithm can essentially provide a smaller transmission delay when expected lifetime is shorter than 8 hours.

9.4 Examples for Multi-path Transmission

We provide two examples for multi-path transmission when the number of transmission paths should be three and four respectively. The base station is in central location.

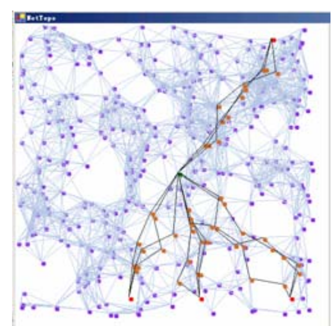

Figure 7. Three paths transmission

In Figure 7 and 8, the red color nodes are source nodes and the green color nodes are base stations. Brown color nodes are relay nodes. The remaining nodes are not involved sensor nodes.

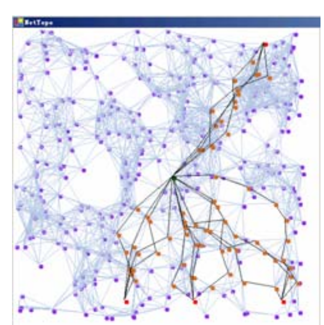

Figure 8. Four paths transmission

10. CONCLUSION & FUTURE WORK

Data gathering problem has received tremendous attentions since the year of 2001. Some applications, such as monitoring an erupting volcano or monitoring a battlefield in frontline in a few hours, motivate the problem for gathering stream data in wireless sensor networks within an expected lifetime. In this paper, we studied two important research problems: 1) maximizing stream data gathering in wireless sensor networks within expected lifetime; 2) minimizing transmission delay for stream data gathering in wireless sensor networks within expected lifetime. The Maximum Stream Data Gathering (MSDG) algorithm and the Minimum Transmission Delay (MTD) algorithm are proposed to solve these two problems. Either of these two algorithms should be run in the initializing phase in every node of whole sensor network for choosing the appropriate transmission radius. When generate rate R of source nodes is larger than the maximum transmission capacity TC of sensor nodes, we find that using node-disjoint multi-path transmission can solve the problem. Simulation results show that our algorithms can essentially solve the identified problems.

Readers are encouraged to download NetTopo Demo from link [25]. In this Demo we guide readers to experience four basic scenarios: 1) Multi-source stream data gathering with dead sensor nodes; 2) Single source multi-path stream data gathering with holes; 3) Multi-source multi-path stream data gathering with holes; 4) Multi-source tree topology based stream data gathering.

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