IEEE Access
SPECIAL SECTION ON ARTIFICIAL INTELLIGENCE FOR PHYSICAL-LAYER WIRELESS COMMUNICATIONS

Received February 25, 2019, accepted May 2, 2019, date of publication May 7, 2019, date of current version May 31, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2915385

An Efficient Information Maximization Based Adaptive Congestion Control Scheme in Wireless Sensor Network

JIAWEI TAN[1], WEI LIU[2], TIAN WANG[3], SHAOBO ZHANG[4], ANFENG LIU[1], MANDE XIE[5], MING MA[6], AND MING ZHAO[1]

[1]School of Computer Science and Engineering, Central South University, Changsha 410083, China
[2]School of Informatics, Hunan University of Chinese Medicine, Changsha 410208, China
[3]College of Computer Science and Technology, Huaqiao University, Xiamen 361021, China
[4]School of Computer Science and Engineering, Hunan University of Science and Technology, Xiangtan 411201, China
[5]School of Computer Science and Information Engineering, Zhejiang Gongshang University, Hangzhou 310018, China
[6]Department of Computer Science, Stony Brook University, Stony Brook, NY 11794, USA

Corresponding author: Mande Xie (xiemd@zjgsuedu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61772554, Grant 61572526, and Grant 61572528, and in part by the Natural Science Foundation of Zhejiang Province under Grant LY17F020032.

ABSTRACT Intelligent communication technology can enhance user experience and improve people's lifestyle. However, due to the limited resources of wireless sensor networks (WSNs), the congestion occurs when the node's traffic load exceeds it's the available capacity. Congestion may cause serious problems such as high packet loss and low throughput, which is an extremely deleterious impact on the performance of WSNs. To tackle this issue, a differentiated rate control data collection (DRCDC) scheme is proposed to avoid or alleviate the network congestion. Different from the previous scheme, the DRCDC scheme can mitigate the congestion by intelligently reducing the data that contains less information, and maintain the distortion rate of information collected by the network is small. The DRCDC mainly avoids or mitigates congestion on the spatial and temporal through information entropy theory, and at the same time makes the information collected by the network has the lowest distortion rate. 1) Congestion mitigation in spatial. Since there is a spatial correlation between sensing data, so in the case of collecting a certain amount of data, some missing data in space can be recovered from another spatially acquired data by matrix completion theory. Therefore, in the DRCDC scheme, when congestion occurs, the amount of data transmitted (forwarded) for nodes are congested will be reduced by an intelligent approach, thereby being able to mitigate congestion. 2) Congestion mitigation in temporal. when congestion occurs, reducing the data collection of time slots containing small information to reduce the flow rate that needs to be transmitted, thereby avoiding congestion while minimizing data distortion rate of the network. The experimental results of the DRCDC scheme in a planar network show better performance than the traditional data collection schemes and reducing the packet loss 2.8%–6.8% while reduce the maximum delay by 34.2%–76.3%.

INDEX TERMS Congestion control, matrix completion, packet loss, delay, wireless sensor networks.

I. INTRODUCTION

With the development of communication network, communication environment is becoming more and more complicated, make traditional communication technologies no longer suitable, and provides many more potential applications of Artificial Intelligence (AI). Intelligent sensor network is widely used in many applications [1]–[3], these applications include industrial field monitoring [4], [5], ecological environment protection [6], [7], intelligent traffic information collection [8], [9], intelligent health monitoring [10]–[13], and location services [14]–[16]. According to [17], after 2011, the number of sensing-based devices connected to the Internet of Thing (IoT) have exceeded the population, reaching 9 billon devices. And it is estimated that by 2020, the number of devices connected to the network will reach 24 billons [17]–[19]. The deployment location of sensing devices is evolved from stationary environmental [20]–[23] to dynamic environmental, for

The associate editor coordinating the review of this manuscript and approving it for publication was Zhanyu Ma.

example, sensor devices in drones and autonomous vehicles [24]–[26], or even sensor-based devices owned by human, such as smartphones [27]–[28]. These sensing devices can be used to detect a multitude of observations, from simple phenomena to complex events [29]–[33]. So many sensing devices sensing from surrounding environment, thus leading to an overwhelming amount of data for sensor-based network [26], [34]–[36]. The amount of data loaded by the sensor node is too large and the data need to be processed can cause many challenge issues for wireless communications [37]–[41]. One of the important challenges issues is congestion in wireless sensor networks (WSNs) [42]–[45]. In WSNs, a large number of low-cost, feature-rich sensor nodes are deployed in area that need to be monitored to sense of the network monitoring area [46]–[48]. Due to the limitation resources of sensor nodes [49], [50], the congestion occurs when the node's traffic load exceeds it's the available capacity [42]–[45]. Congestion may cause serious problems such as high packet loss and energy consumption, and low throughput, which is extremely deleterious impact on the performance of WSNs [42]–[45]. Researchers have proposed many methods to tackle this issue. This kind of research can be mainly divided into the following two types of methods:

(1) Research on mitigating (avoiding) network congestion based on rate control [42], [43], which is the earliest, most extensive, and most direct method. The working principle of rate control is: when congestion occurs, the system detects the source flow upstream of the congestion occurrence area, reducing the rate of source flow according to congestion control scheme, so that the congestion can be mitigated and eliminated. This method is one of the most natural and most commonly used methods, which involves less control parameters, by reducing the rate of the source flow in advance, thereby avoiding the waste of network energy and processing power when the partially overloaded flow is dropped due to transmitted to the congestion node. However, the shortcoming of this method is that only consider drop packets to reduce the rate and does not distinguish the content of the packet, which may cause the drop of the important packet to cause significant damage to the quality of the network monitoring. In fact, the amount of information contained in packets by different nodes in the sensor network is different, for example: in the monitoring of unexpected events such as ultra-high pressure, ultra-high temperature, even fire in industrial boilers, the amount of data perceived by nodes near those events contains the most information and the most important. The loss of these packers can cause serious damage to the monitored objects, such as boiler explosions, casualties and other serious consequences. And the data that is perceived by the node not in these events area will not damage the system even if it is not transmitted to the sink. This is because these packets contain less information and are not important, so even if they are missing, they will not affect the decision of the system. In the rate control-based congestion avoidance scheme, the control of the data flow does not distinguish the content of the packet, that is, in order to avoid congestion, drop some packets without considering the contents of the packet, so that the source flow rate is within the controllable range. Therefore, in this scheme, it is possible to drop the data packet containing a large amount of information, and the data packet that is transmitted to the sink is less information, and the drop of the important data packet causes the sink to not effectively reconstruct the network information, thereby causing the application to suffer losses.

This shows that the importance of the information by the data packet should be considered comprehensively when designing the congestion avoidance scheme. When congestion occurs, it should be optimized from the following two aspects: one is when the network is congested, the data collected by the sensor node should contain the largest amount of information, and avoid collecting data packets that do not help the reconstruction event, thereby reducing the transmission amount of the data packet from the data source. Therefore, the collection of data packets from the source, the energy consumed and resource consumption of the data packets are reduced, and the effect of the network performance is minimized. The other is when congestion occurs, the packets that have the least effect on the rebuild event should be dropped, so that the network can maintain a high level of event reconstruction performance while avoiding congestion.

(2) Based on detour scheme to avoid the congestion area. The idea of this type is to try to make the data flow bypass the congestion area when the network congestion occurs, and reach the sink through the non-congestion area [44], [45]. Obviously, the advantage of this method is not to use drop data as the main control method, but to avoid the congestion to achieve the goal of congestion control. Therefore, in this method, the data is dropped less, and the quality of event reconstruction is better. However, this method has the following disadvantages: (a) When the congestion occurs, the routing path that avoids the congestion can be found. If the entire network is congested, the method becomes unavailable. (b) It is need to cost extra resource to monitor the resource consumption of the network. This method needs to monitor the load status of the node, so as to know the resource and load status of different nodes in the network, and to monitor the status of the network node requires the sending and transmitting of the message, which additionally increases the load of the network and consumes the network resources. On the other hand, the load situation in the network is constantly changing, so if the monitoring data is inaccurate, the effect of congestion avoidance is not ideal. (c) Finally, the routing scheme designed of data flow in wireless sensor networks generally follows the scheme of minimizing energy consumption and minimizing delay. The bypass scheme that avoids congestion area generally increases the length of the data route, which consumes more energy and causes more delay, resulting in reduced network performance.

In summary, there are still some shortcomings in these two schemes with congestion control. The advantage of the detour-based congestion scheme is that it does not drop packets but bypasses the congestion area to achieve the purpose of congestion avoidance. Therefore, the system loses less information and thus is beneficial to the system decision. However, the shortcoming of this method is that the system costs more. First, the system needs to monitor the load of the network, which is a systematic monitoring operation, thus consuming a large amount of resources on the network. In addition, the detour scheme increases the length of packet routing, which increases delay, resource consumption, etc. And the method based on rate control is relatively a "rough" method. The advantage is that the control is simple, the effect is obvious, and the resources consumed are relatively small. However, the biggest shortcoming if this method is that the data packet is lost without considering the importance of the data packet, so that important data packets may be dropped and cause significant system loss. In summary, it can be seen that the design of the congestion scheme that resource consumption is low, the efficiency is high, and can maximize the amount of information obtained by the system is a challenge issue. In this paper, a differentiated rate control data collection (DRCDC) scheme is proposed to avoid or mitigate the network congestion under the condition that the data center collects the packets that contain the maximum information and the low cost of the system. DRCDC scheme changes the lack of prioritization of control over the importance of data packets in previous schemes. DRCDC scheme achieves the purpose of avoiding congestion by reducing the amount of information containing less information collected by using information entropy in spatial and temporal to keep the information collected by the network with a small distortion rate. Specifically, the innovations of this paper are as follows:

(1) The DRCDC scheme innovatively proposes a differentiated rate control congestion avoidance design by using matrix completion technology, thus avoiding congestion on the premise of maximizing the amount of information collected. First, because there is a spatial correlation between sensing data, therefore, based on the matrix completion technology, the spatially related data sample can be compensated by increasing the data samples of the non-congestion area and collecting the data of the congestion area as long as the amount of data requirement of the matrix completion is satisfied. This will ensure that congestion is avoided if there is no loss of information collected by the system. Secondly, in our proposed scheme, according to the matrix completion theory, the collection of data in partial regions can be reduced, thereby reducing the amount of data collected overall, thus reducing the probability of occurrence of congestion. To sum up, the DRCDC scheme proposed in this paper can avoid the congestion based on the overall reduction of data traffic, and ensure that the system collects maximum information. This is the first innovation point that distinguishes the previous scheme.

(2) The second innovation point of the DRCDC scheme is to propose a congestion avoidance method based on temporal entropy minimization. Data samples not only have spatial correlation, but also have correlation in temporal. Therefore, by optimizing the collection time point of data samples, reducing the amount of data sample when the node is congested, and appropriately increasing the amount of data when the node is uncongested. It is possible to reduce the amount of data and avoid congestion under the premise of maximizing the collected data information, thereby better reducing the packet loss rate of the network and reducing the delay of data packet transmission.

(3) The DRCDC scheme has better performance than the previous. When the number of collected data is the same, the DRCDC scheme can not only mitigate the network congestion, reduce the packer loss rate and delay of network transmission, but also guarantee the data quality of the collected data. The DRCDC adopts a time and space differentiated rate control method, which can better mitigate the congestion of nodes in a subtree with high congestion probability. And the energy consumption of the bottleneck node in high congestion probability subtree is higher than that of the bottleneck node in low congestion probability subtree. Therefore, The DRCDC scheme has little impact on the network lifetime. In this paper, the performance evaluation and verification of the DRCDC scheme is carried out through simulation experiments, and the simulation implementation is performed using omnet++. The experimental results show that the delay optimization is above 34.2%, the packet loss rate is reduced by 2.8%−6.8%, and the collected data quality is guaranteed.

The rest of paper is organized as follows. Section 2 summarizes the related work. The problem description and system model are defined in Section 3. In Section 4, we propose an unbalanced data distribution scheme in detail. The theoretical analysis and simulation results are presented in Section 5. Section 6 concludes the paper.

II. BACKGROUND AND RELATED WORK

Congestion is a phenomenon that often exists in the network. It refers to the phenomenon that the amount of data transmitted by the network and the load of the router in the network exceeds the rate at which it can be transmitted, causing the data of the buffer to overflow. This phenomenon first appeared in the Internet. With the development of optical fiber communication and the development of microprocessor technology, the communication capacity and the data forwarding capability of the router have been increased by orders of magnitude. Therefore, the congestion of the wired network is greatly mitigated. However, the wireless network is another situation. With the development of the Internet of Things (IoT), the number of sensing devices grows geometrically, which leads to network traffic and computing resources to the edge of the network. Edge computing and Fog network is the new computing model and network for this situation. Due to the tremendous growth of sensing devices, and the variety of the perceived data, the scale grows faster, which leads to network congestion being more common in wireless networks. However, it appears more frequently in wireless sensor networks. This is because the sensor nodes in the wireless sensor node network have less storage capacity, and the processing capacity of the nodes is limited. More importantly, the sensor network is mainly for the monitoring of events. Due to the suddenness and mass occurrence of events, when an event occurs, it will often cause related events to occurs, so that the data to be transmitted is often sudden and massive. Therefore, congestion is easy to occur, and when congestion occurs, the important data is need to be transmitted. When there is no emergency event, its data is ordinary data. When a congestion occurs, it will cause significant damage to the application. Therefore, Congestion avoids the study of slow resolution is of great significance. Related research work is also a lot.

The congestion control method based on rate control is the most widely used method. Congestion control methods using rate control are mainly concentrated in two aspects, one is centralized rate control, and the other is distributed rate control.

The centralized rate control method mainly uses the sink to adjust the frequency at which each node generates packets or the rate of its send link. ESTR [42] adjusts the data generation rate of each node according to the reliability of each node transmitted to the sink path. The reliability of each node is measured by the packets successfully received by sink. By reducing the data generation rate of nodes with lower reliability, the network congestion is mitigated, and since the number of retransmissions of the low reliability path is greater than that of the high reliability path, this method also reduces the energy consumption of the network. In Ref. [51], a centralized rate control method is also used. The sink detects whether the node is congested and adjusts the rate of its transmission link. The rate is adjusted by means of AIMD (Additive Increase – Multiplicative Decrease) [51]. It determines the multiplicative decrease factor according to the reliability of each node's path to the sink. The path with high reliability and the multiplicative decrease factor are correspondingly higher, so when the congestion occurs, the rate reduction will be smaller.

Another way of rate control is distributed. The distributed rate control method mainly determines the frequency of the data packets generated by the sensor nodes and the transmission link rate. In Ref. [52], the node checks the buffer length of the node to determine whether the node will be congested. A buffer threshold is set. When the data packet stored in the node exceeds the buffer threshold, the lower priority packets are preferentially dropped. And each node monitors the forwarding delay of the data packet at the next hop node after transmitting the data packet to the next hop node, compares the forwarding delay with the delay stored in the node, and takes a larger forwarding delay. When the network is detected to be congested, the rate of packet generation is reduced. The greater the forwarding delay recorded in the node, the lower the rate of packet generation. However, this method has a serious problem. Because the node is congested, the packet with lower priority will be dropped, so it is possible that the packet with lower priority will never be received. In [53], a fairness-based congestion control method is proposed. The storage queue of the sensor node is divided into three queues, which are high priority queue, medium priority, and low priority queue. Each time a packet is received, the priority of the packet is discriminated by a classifier and stored in the corresponding queue. When sending data, if both queues want to send data at the same time, a collision will occur. In this method, the data of the queue with higher priority will be sent, and the data of the queue with lower priority will continue to be stored in the queue. When a queue with a lower priority is collided with a queue with higher priority and the data is not successfully transmitted, the priority of the packet is doubled, and the priority is redetermined. In this way, each priority class packet can be transmitted.

However, the rate control method reduces the data quality by the last collected data whether it reduces the node's generated rate or the number of transmitted packets at the relay node. In [54], a routing method that tolerates data loss is proposed. Each node is set with a tolerant estimation error, and the current time data value is estimated by storing the value of the previously forwarded data, and the current data is calculated, and the success rate of the last hop node transmission is determined by the current estimation error. Reducing the current estimation error by successfully transmitting data. Therefore, it also guarantees the estimation error of the entire network. Based on this idea of guaranteeing the estimation error of each node to ensure the overall estimation error of the network. In [55], a congestion control method is proposed to ensure the error of each node to ensure the overall error of the network. By detecting the queue of itself, it is judged whether the node is congested. If congestion occurs, the data in the queue is grouped by k-means. And each group is compressed and aggregated, thereby reducing the amount of data stored in the queue, thereby mitigating the congestion of the network under the premise of ensuring the estimation error of the entire network.

However, although the previous method has considered data collection under the premise of tolerating estimation error, it is to ensure the estimation error of the data collected by the entire network by ensuring the estimation error of a node. However, the distribution of data can also affect the quality of the data collected last. Matrix completion technology is a technique that can recover the entire matrix from the matrix of missing data. The recovery error has a great relationship with the distribution of data in the matrix. It is generally believed that when there is no row in the matrix does not collect data, the reconstruction error of the matrix will be very large [56]. There are already many studies that study the relationship between reconstruction error and data distribution after recovery.

Cheng *et al.* [57] proposed a data collection scheme called STCDG. In the process of data collection, STCDG and the previous data collection scheme are similar, still collect data according to a sampling rate. However, after the collection is completed, the STCDG scheme first extracts all the non-empty columns from the collection matrix to form a new matrix, and then uses matrix completion to recover the new matrix. After the recovery, the previous empty columns are inserted into this matrix in chronological order. Since the data has short-term stability in time, these data can be recovered by semi-planning. the reconstruction error of the matrix is small.

In [44], the author studies the relationship between information entropy and reconstruction error. The entropy of the matrix can be expressed as the uncertainly of the matrix. the lower entropy of data matrix, the lower reconstruction error after matrix completion recovered. And this has been verified by a large number of experiments.

The method described above is mainly based on the method of rate control. Another way to control congestion is to avoid the method of congestion. In such a method, when congestion occurs, the routing path avoiding the congestion area is searched from the source direction of the data flow. Since the data flow of the congestion area no longer flows to the congestion area, the data flow of the congestion area is decreased, thereby mitigating or even eliminating the congestion. It can be seen that the advantage of this congestion control method is that it does not drop packets as the rate control, but bypasses the congestion area mainly through other routing paths. Although there will also be congestion when routing to other routing paths, or because the overall network load is too heavy to find a route that avoids congestion, it will also cause data to be dropped. However, the probability of this situation appearing in the method of avoiding congestion is not high. Therefore, the congestion avoidance method has small error in event reconstruction due to the dropping of few packets. However, this method also has its shortcomings. The main drawback is that the network needs to monitor the load of the node in peacetime, so that when the congestion occurs, it can find the path to avoid the congestion. Monitoring the load of the node requires consuming extra resources of the network, thereby increasing the load and energy consumption of the network and reducing the network lifetime. And because the monitoring of this node load situation is a system behavior of the network, its system cost is very large. In addition, this method of bypassing the congestion also increases the packet routing length, thereby increasing the resource consumption of the routing. And in process of detouring, the resource consumption of other area is also increased, resulting in unbalanced resource consumption of the network. In some cases, congestion occurs when detouring, thereby deteriorating network performance.

In summary, to design a congestion control that network system resources consumption is small, the congestion control effect is good, and the loss of information collected by the network is as small as possible is a challenge issue.

III. THE SYSTEM MODEL AND PROBLEM STATEMENT

A. THE NETWORK MODEL

The network model used in this paper is similar to [37]. N nodes are randomly and uniformly deployed in a circle of radius R. Each node has a unique node id and knows its own coordinates (x_i, y_i) and the position of the sink.

The maximum transmission radius of each node is r, and the transmission radius is limited, and the data packet needs to go through multiple hops to reach the sink. In order to reach the sink as soon as possible, a fixed shortest path is used [37]. The shortest path is established by means of broadcast diffusion [37]. Each node stores a hop count h_s from the sink. In the initialization phase, h_s of all nodes is set to infinity. sink sets its own h_s to 0 and broadcasts an INIT message containing a value of $h_s^{'} = h_s + 1$. When the node receives the INIT message, the comparison node h_s and $h_s^{'}$, when $h_s^{'} < h_s$, set the hop count h_s to $h_s^{'}$, establish a route from the node to the broadcast source node, and continue to broadcast an INIT message in the same way as before, until the broadcast message is no longer generated in the network.

After the route is established, the network will form a shortest path tree with sink as the root node. The hop count of each node reaching the sink is its depth. Each node periodically generates packets and transmits them to its parent node until the data packet reaches the sink.

B. THE MATRIX COMPLETION MODEL

The matrix completion technique used in this paper is similar to [56]. Matrix completion technology can recover all data from a low rank matrix with missing data. Considering a matrix X of size $N_1 \times N_2$, where N_1 represents the number of sensor nodes and N_2 represents the number of cycles in which data is collected.

$$X = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,N_2} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,N_2} \\ \vdots & \vdots & \ddots & \vdots \\ x_{N_1,1} & x_{N_1,2} & \cdots & x_{N_1,N_2} \end{bmatrix}$$

Considering that the collected data set is Ω, then the data collection process $P_\Omega(X)$ is:

$$P_\Omega(X) = \begin{cases} x_{i,j} & (i,j) \in \Omega \\ 0 & otherwise \end{cases}$$

Considering M is a matrix that satisfies the irrelevance and low rank, matrix completion can be transformed into the following optimization problem [56]:

$$\begin{aligned} &minimize\ rank(X) \\ &s.t. P_\Omega(X) = P_\Omega(M) \end{aligned}$$

But the rank minimization of the matrix is an NP-hard problem. Similar to compressed sensing, the L1 norm is replaced by the L0 norm, and the matrix completion is used to solve the rank of the solve matrix by solving the kernel norm. Then the problem changes to

$$\begin{aligned} &minimize\ \|X\|_* \\ &s.t. P_\Omega(X) = P_\Omega(M) \end{aligned} \tag{1}$$

where $\|X\|_*$ represent the kernel norm of matrix, $\|X\|_* = \sum_{k=1}^{n} \sigma_k$, σ_k is the k^{th} singular value of the matrix arranged from largest to smallest.

However, the method of kernel norm optimization is constrained by the lowest rank matrix condition [58], resulting in unsatisfactory results of recovery. Therefore, A simple matrix completion algorithm for larger scale matrices is proposed in [58]: Singular Value Thresholding (SVT) algorithm. It solves the equivalence problem of Eq. (1):

$$\begin{aligned} &minimize\ \tau \|X\|_* + \frac{1}{2}\|X\|_F^2 \\ &s.t. P_\Omega(X) = P_\Omega(M) \end{aligned} \tag{2}$$

Obviously, when τ tends to infinity, the solution of problem (2) approaches the solution of the original problem (1). The essence of the SVT algorithm is a Lagrangian multiplier method, and its Lagrangian function is:

$$L(X, Y) = \tau \|X\|_* + \frac{1}{2}\|X\|_F^2 + < Y, P_\Omega(X) - P_\Omega(M)$$

where $< X, Y >$ represent the scalar product between two matrices.

Reference [58] proves that the best advantage of this Lagrangian function is the same as that of its Lagrangian dual function. The best advantage of the dual function can be obtained by the following iteration:

$$\begin{cases} L\left(X^k, Y^{k-1}\right) = L\left(X, Y^{k-1}\right) \\ Y^k = Y^{k-1} + \delta_k P_\Omega\left(M - X^k\right) \end{cases}$$

For a matrix X of rank r, its SVD is decomposed into

$$X = U\Sigma V^T, \Sigma = diag(\{\sigma_i\}_{1\le i\le r})$$

Then the singular value contraction operator is defined as:

$$D_\tau(X) = UD_\tau(\Sigma) V^T, \quad D_\tau(\Sigma) = diag(\{\sigma_i - \tau\}_+)$$

where $t_+ = \max(0, t)$.

Therefore, the iterative equation of the SVT algorithm can be finally obtained as

$$\begin{cases} X^k = D_\tau(Y^{k-1}) \\ Y^k = Y^{k-1} + \delta_k P_\Omega\left(M - X^k\right) \end{cases}$$

C. PROBLEM STATEMENT

The main purpose of this paper is to design a data distribution scheme to mitigate network congestion, reduce network packet loss rate, reduce network transmission delay, and ensure data quality of collected data. The scheme has the following characteristics:

(1) Improve the network lifetime. The network lifetime is related to the node with the most energy consumption in the network. When the energy stored in one node is exhausted, the node cannot work normally, which will cause the network to fail to achieve its normal function, that is, the network is paralyzed. Definition ℓ is the network lifetime. The energy consumption of each node receiving one packet is E_R, and the energy consumption of sending one packet is E_T. It is considered that the number of data packets received by node i is a_i, and the number of sends is b_i. The node set is S, and the network lifetime can be expressed as:

$$\max(\ell) = \min(\max_{i\in S}(a_i E_R + b_i E_T))$$

(2) Reduce network packet loss rate. There are two main reasons why packets are lost in transmission: The first one is due to noise interference in the transmission link, which causes the packet to be lost. The second is due to the packet storage queue is full in the network, resulting in packet loss caused by the data packet cannot be forwarded. Congestion caused by the first case is difficult to avoid. The retransmission mechanism is usually used to ensure its reliability. The data packet is retransmitted until the target node successfully receives the data packet or retransmits it to the maximum number of times. Defining the packet loss rate of the network is d, the number of packets generated by each node i is ω_i, and the number of packets received by sink is χ_i, and the packet loss rate of the network can be expressed as:

$$\min(d) = \max(\sum\nolimits_{i\in S}\chi_i / \sum\nolimits_{i\in S}\omega_i)$$

(3) Reduce the maximum delay of network transmission. The delay of the network refers to the time elapsed from the generation of the packet until it is received by the sink. The delay of the network is mainly composed of the time when transmitting in the link and the waiting time in the sending queue. The maximum delay for defining the network is $\mathcal{D}$, the set formed by relay nodes of the packet transmission is $\mathcal{T}$, and the time for each relay node i to successfully send packet is υ_i, and the time waiting for transmission in this node is φ_i, the maximum delay of the network can be expressed as:

$$\min(\mathcal{D}) = \min\max_{i\in S}(\sum\nolimits_{j\in\mathcal{T}_i}(\upsilon_j + \varphi_j))$$

To sum up, the optimization goal of the proposed scheme is as follows:

$$\begin{cases} \max(\ell) = \min(\max_{i\in S}(a_i E_R + b_i E_T)) \\ \min(d) = \max(\sum_{i\in S}\chi_i / \sum_{i\in S}\omega_i) \\ \min(\mathcal{D}) = \min\max_{i\in S}(\sum_{j\in\mathcal{T}_i}(\upsilon_j + \varphi_j)) \end{cases}$$

IV. THE DESIGN OF DRCDC SCHEME

A. RESEARCH MOTIVATION

In the data collection network, after the route is established, the nodes periodically generate packet and transmits it to its parent node, and finally transmits to the sink through multiple hops. Therefore, when the data transmission rates are the same, since multiple child nodes transmit data to their parent node, and the parent node only one send path, so the data will accumulate in the node until the node's storage queue is full. Therefore, the node is congested, when the node is congested, it is unable to receive packets, increase the transmission delay, and even packet loss.

Fig. 1 is in $M/M/1/m$ queue model, the probability of node congestion. the ρ represents the ratio of input rate to

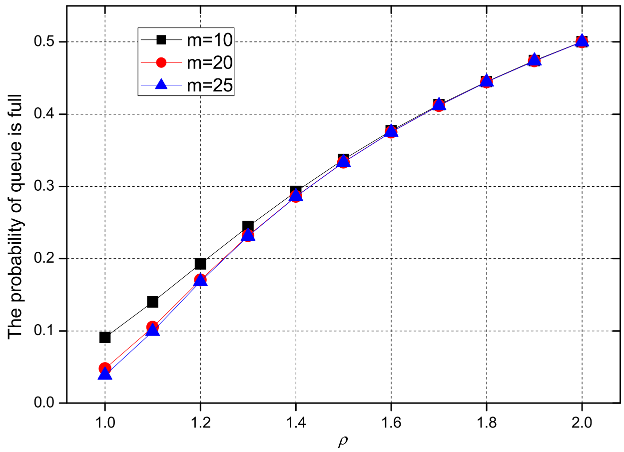


FIGURE 1. **The probability of congestion.**

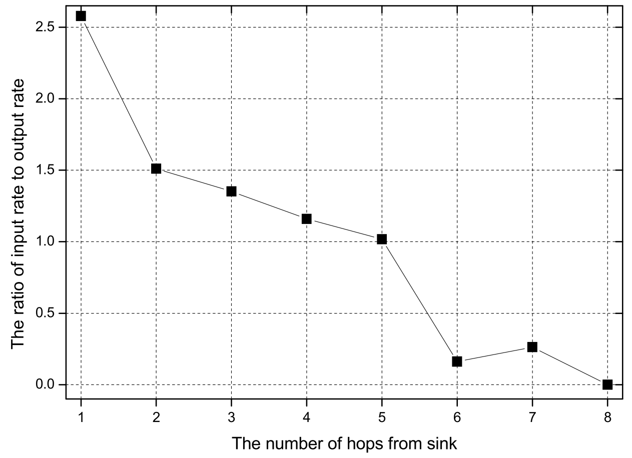


FIGURE 2. **The ratio of input rate and output rate.**

output rate, the probability of node congestion increases as the ratio of input rate to output rate. And when the ratio of input rate to output rate is larger, the size of storage queue has not been able to effectively reduce the probability of node congestion. Therefore, mitigating or avoiding network congestion requires reducing the ratio of input rate to output rate.

Based on some data recovery techniques, the data can be recovered from the data received. Therefore, the node's generate rate can be reduced to reduce the ratio of input rate to output rate, thereby mitigating network congestion.

In the traditional congestion control scheme-based matrix completion technology, when the number of collected data is constant, the probability of each node generating packet is the same. And since the probability of each node generating packet is same, the number of packets generated by each node is similar. However, the probability of congestion on each node in the network is different. Randomly distribute 500 sensor nodes, establish the shortest path, and get the ratio of input rate to output rate of each node is as Fig. 2.

It can be seen that the ratio of input rate to output rate is different in different areas. Obviously, the ratio of input rate to output rate is high, and the probability of congestion at this node is higher. Therefore, the probability of congestion is different at different nodes. However, in the traditional scheme based on matrix completion technology, the generated rate of each node is similar. Thus, some nodes will be congested, while some nodes will not be congested, and the nodes that are congested will randomly lose a large number of packets, reduce the data quality of the collected data, and increase the reconstruction error of the received data.

Therefore, it is necessary to design a data collection scheme to reduce the reconstruction error of the collected data and to mitigate the congestion of each node in the network. Thus, when the node is congested, reducing the generated rate of nodes in its subtree, and to ensure the data quality of the collected data, appropriately increase the generated rate of the other nodes that do not have congestion. thereby adaptively adjust the generated rate of each node to mitigate network

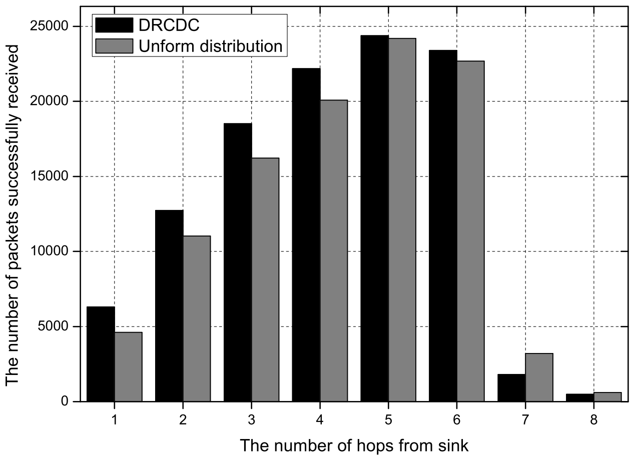


FIGURE 3. **The number of packets successfully received by sink.**

congestion. The number of packets successfully sent by the node after adjustment is shown in the Fig. 3, it can be seen that in the scheme of adaptively adjusting the generated rate of the node (DRCDC), the number of successfully transmitted packets is more than the scheme without adjusting the generated rate.

Fig. 4 shows the transmission success ratio of each node under a fixed sampled number. It can be seen that in the scheme with adaptively adjusted generated rate (DRCDC), the transmission success rate of each node is high. And in the traditional method with the fixed generated rate of the node, the farther the node is from the sink, the lower the transmission success rate. That is, the packets are lost during the transmission process.

The packets lost during transmission are random, and random loss of packets will seriously reduce the information contained in the collected packets, and increase the reconstruction error after using matrix completion technology. The average entropy can measure whether the information collected is sufficient (detailed in Section 4.3). The average entropy is shown in Fig. 5. Since the congestion condition

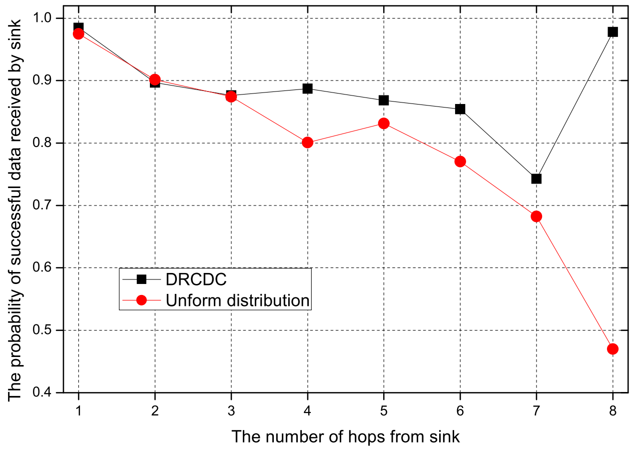


FIGURE 4. The delivery success rate of each node.

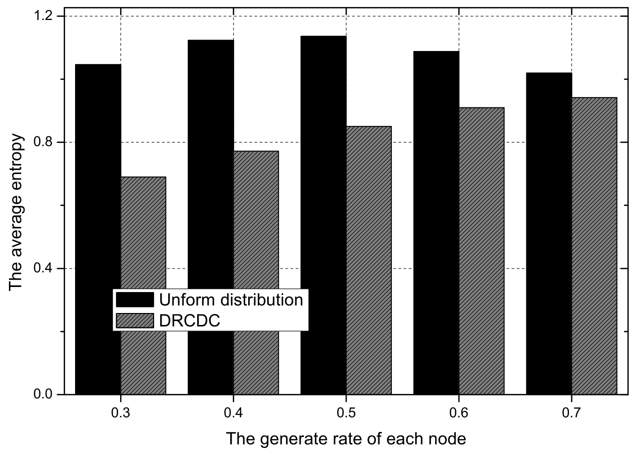


FIGURE 5. The average entropy of matrix before collecting.

in the network is mitigated after the adaptive adjustment, the method of adjusting the generated rate is lower than the average entropy of the method of not adjusting the generated rate. And the lower the average entropy, the lower the reconstruction error after recovered [44]. Therefore, it can reduce the reconstruction error of the recovery matrix and improves the data quality of the collected data.

Above all, the rate control method that adaptively adjusts the generated rate of each node can adapt to different environments of different networks, mitigate network congestion, reduce the reconstruction error of the recovery matrix, and improve the data quality of collected data.

B. OVERVIEW OF THE PROPOSED SCHEME

The main purpose of this paper is to propose a data collection method to mitigate the congestion of network by adaptively adjusting the generated rate of each node, reduce the reconstruction error of recovery matrix, and ensure that the network lifetime is not reduced. Since the matrix completion technology can tolerate the loss of a part of data, the performance of the network is optimized by reducing the number of packets generated by the source node.

When using rate control to mitigate network congestion, reducing the data generated by the source node will reduce the data quality and increase estimation error. Therefore, the estimation error is needed to be considered. The reconstruction error of the data matrix is highly correlated with the distribution of the data in the matrix. The entropy of a matrix is a parameter that can measure the uncertainly of a matrix. In the data matrix, the rows of the matrix represent the packets generated by the same sensor node in different periods, and the same column represents the packets generated by different sensor nodes in the same cycle. Obviously, the data collected by the same node has a strong correlation in temporal. The temporal correlation of data is represented by temporal entropy. When the temporal entropy of a node is smaller, the data uncertainly in this sensor node is lower. The entropy of a collection point in a sensor node is related to its mutual information. The larger the mutual information, the smaller the temporal entropy of the node, and the mutual information is related to the interval between the collection point and the known collection point. the larger the interval, the smaller the mutual information of collection point (detailed in Section 4.3). Therefore, when the number of packets generated by a sensor node is constant, an appropriately data distribution scheme can maximize the mutual information of the collection point with uncollected data in a sensor node, thereby minimizing the temporal entropy.

In spatial, since the numbered adjacent sensor nodes spatially related in the matrix, the distance between adjacent nodes is not necessarily the smallest, and the distance between adjacent nodes cannot be minimized. Therefore, it is difficult to control the spatial entropy of a matrix. And in data collection matrix, there is another problem, the problem of network congestion. When the transmission rates are the same, since the number of nodes in the near sink is definitely much smaller than the number of nodes in far sink, the nodes near the sink must have multiple receiving routes path, so the receiving rate of node is greater than the sending rate, and congestion may occur.

Therefore, a differentiated rate control scheme is adopted. When a node is congested, increase the data generation interval of all nodes in its subtree. However, increasing the data generation interval increases the number of uncollected packets and increases the average entropy interval of the matrix. Therefore, after the congestion node increases the data generation interval, a congestion message is transmitted to its parent node, and the parent node reduces the data generation interval of other non-congested nodes, thereby increasing the number of data generation of the non-congested node. The average entropy of the collected data is reduced as much as possible.

Fig. 6 is the shortest path tree formed by the algorithm according to the shortest path. The root of the shortest path tree is sink. When the node numbered 2 is congested, increase the data interval of the subtree of the node numbered 2 to generate data. At the same time, sending a congestion message to its parent (node numbered 1), after its parent node receives the

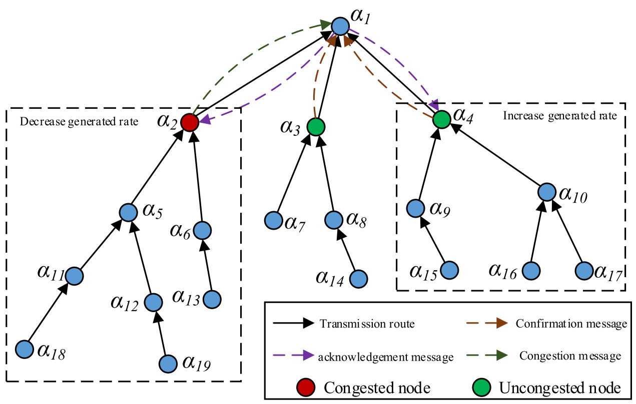


FIGURE 6. The description of DRCDC scheme.

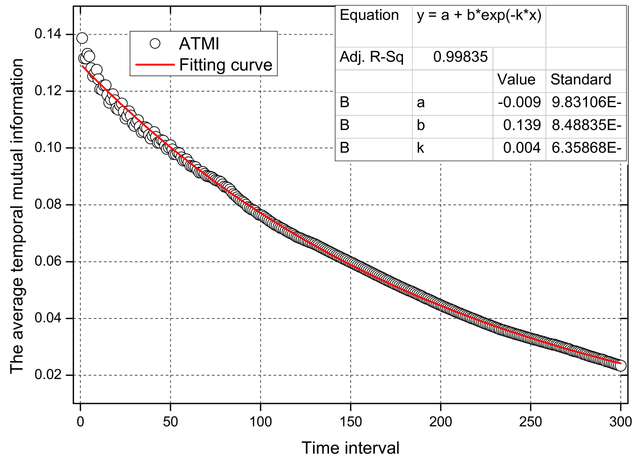


FIGURE 7. The average temporal mutual information.

congestion message, it reduces the data generation interval of the non-congested node (Such as: nodes in the subtree rooted at node numbered 4 in Fig. 6). Thereby mitigating network congestion, and also ensuring the total number of packets collected by the network, thus ensuring the average entropy of matrix.

C. MINIMIZING ESTIMATION ERROR

In order to minimize estimation error, we want to collect the packets that contain as much information as much possible. the more information contained by collected packets, the lower the reconstruction error after using matrix completion recovered. It is generally considered that the collected data is randomly and uniformly distributed with low error [56].

1) TEMPORAL ENTROPY

The uncertainty of sampling can be expressed by entropy. The more data collected randomly, the lower the reconstruction error of the matrix. Therefore, the entropy is used to estimate the error after recovery of the matrix. According to the definition of entropy, the lower the uncertainly of the event. The higher the entropy, the higher the uncertainly of the event.

Considering that the matrix X has a total of k states, the temporal entropy at time slot t can be expressed as:

$$H_T(t) = -\sum_{i=1}^{k} \Pr(i,t) \cdot \log(\Pr(i,t))$$

where $\Pr(i,t)$ is the probability that state i appears in the t^{th} slot. Considering $N_{i,t}$ is the number of occurrences of state i in the t^{th} slot, and $\Pr(i,t)$ can be represented as $N_{i,t}/n$, n is the number of rows of matrix X. Therefore, the mutual information of the same node at different time slot can be expressed as:

$$I_T(t_1,t_2) = H_T(t_1) + H_T(t_2) - H_T(t_1,t_2)$$

where $I_T(t_1,t_2)$ represents the mutual information between time slot t_1 and time slot t_2, that is, the information loss of the t_2 when the t_1 is known (or the information loss of the t_1 when the t_2 is known). Obviously, the closer between two time slots, the larger the information loss. Thus, the average temporal mutual information with the interval k_T is defined as follows:

$$M_T(k_t) = \frac{1}{m-k_t}\sum_{i=1}^{m-k_t} I_T(t_i,t_{i+k})$$

The data is from Intel Berkeley Research Lab [59], the collected data is started at February 28, 2004, and collected data every hour. Therefore, a total of 739 rounds of data collected. And 52 sensor nodes with complete data is selected to construct a matrix X_f with size of 52×739.

Based on the fitting tool of OriginPro [60], the average mutual information of the matrix X_f at different time interval. The selected fitting function is $y = be^{-kx} + a$, the fitted parameters is shown in Fig. 7. Therefore, the mutual information at different time slot $I(t_1,t_2) = M_T(|t_1-t_2|)$.

Furthermore, the conditional entropy can be obtained as follow:

$$H_T(t_1\,|\,t_2) = H_T(t_1) - I(t_1,t_2) \tag{3}$$

The mutual information can be calculated by the formula $I(t_1,t_2) = M_T(|t_1-t_2|)$, so the condition entropy is as follow:

$$H_T(t_1\,|\,t_2) = H_T(t_1) - M_T(|t_1-t_2|)$$

Considering that the sample set of the matrix is Ω, so the set of all sample points is $\{x_{i,j}|(i,j)\in\Omega\}$. The temporal entropy of each sample point is expressed as $H_T(x_{i,j}|x_\Omega)$. In the same node, the adjacent sample points are considered. Therefore, the temporal entropy of the sample point $x_{i,j}$ can be expressed as:

$$\bar{H}_T(x_{i,j}\,|\,x_\Omega) = \frac{H_T(x_{i,j}\,|\,x_{i,kl}) + H_T(x_{i,j}|x_{i,kr})}{2}$$

where $kl = \max\{k, |x_{i,k} \in \Omega \& k < j\}$, $kr = \max\{k, |x_{i,k} \in \Omega \& k > j\}$. Substituting Eq. (3), can get:

$$\bar{H}_T(x_{i,j}\,|\,x_\Omega) = H_T(x_{i,j}) - \frac{M_T(|j-kl|) + M_T(|\text{kr-j}|)}{2}$$

2) SPATIAL ENTROPY

Similar to the temporal entropy, l denote the sensor node numbered l, and the spatial entropy can be defined as:

$$H_S(l) = -\sum_{i=1}^{k} \Pr(i, l) \cdot \log(\Pr(i, l))$$

The mutual information between different sensor nodes is expressed as:

$$I_S(l_1, l_2) = H_S(l_1) + H_S(l_2) - H_S(l_1, l_2)$$

The spatial entropy is as:

$$H_S(l_1 \mid l_2) = H_S(l_1) - I_S(l_1, l_2)$$

However, the spatial mutual information is processed in the same way as processing temporal mutual information, and the spatial mutual information does not decrease as the interval increased. This is as the interval k increases, the distance between the two nodes does not necessarily increase. Therefore, the spatial mutual information is not related to the length of interval, so the method of fitting is also not applicable.

Considering that $x_{i,j}$ is a sample point, the spatial entropy of $x_{i,j}$ is $H_S(x_{i,j}|x_\Omega)$, then

$$H_S(x_{i,j} \mid x_\Omega) = H_S(x_{i,j}) - I_S(x_{i,j}, x_{l,j})$$

where $l = \max\{k \mid \max(I_S(l_k, l_i)) \, \&\& x_{k,j} \in \Omega\}$.

3) THE AVERAGE ENTROPY

The uncertainly of the collection matrix is from uncollected data, and the entropy of the collected data should be 0. Therefore, $a_{i,j}$ is used to represent whether the collection point is collected ($a_{i,j} = 1$ represent the collection point is collected, and $a_{i,j} = 0$ represent collection point is uncollected). Thus, the entropy of the matrix X with size is $N \times M$ can be represented as:

$$H_\Omega(X) = \sum_{i=1}^{N} \sum_{j=1}^{M} (1 - a_{i,j}) H(x_{i,j}|x_\Omega)$$

where $H(x_{i,j}|x_\Omega)$ is the condition entropy. It is difficult to calculate the condition entropy directly, so the entropy is replaced with temporal entropy and spatial entropy. Therefore, the entropy of matrix is as:

$$\begin{aligned} H_\Omega(X) &= \sum_{i=1}^{N} \sum_{j=1}^{M} (1 - a_{i,j})(H_T(x_{i,j} \mid x_\Omega) + H_S(x_{i,j} \mid x_\Omega)) \\ &= H_{T,\Omega}(X) + H_{S,\Omega}(X) \end{aligned}$$

Furthermore, the average entropy can be expressed as:

$$\bar{H}_\Omega(X) = \bar{H}_{T,\Omega}(X) + \bar{H}_{S,\Omega}(X)$$

where

$$\bar{H}_{T,\Omega}(X) = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} (1 - a_{i,j}) H_T(x_{i,j}|x_\Omega)}{\sum_{i=1}^{N} \sum_{j=1}^{M} a_{i,j}}$$

$$\bar{H}_{S,\Omega}(X) = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} (1 - a_{i,j}) H_S(x_{i,j}|x_\Omega)}{\sum_{i=1}^{N} \sum_{j=1}^{M} a_{i,j}}$$

Therefore, the average entropy of matrix can be obtained. The average entropy is related to the uncertainly of matrix, When the average entropy is higher, the uncertainly of the matrix is larger, so the reconstruction error of matrix is larger. When the average entropy is low, the uncertainly of matrix is low, so the reconstruction error of matrix is low. In [44], the authors proved this feature of average entropy by a large number of experiments. Therefore, the average entropy should be as small as possible to reduce the reconstruction error.

Theorem 1: When K packets is collected at a sensor node, and a total of M time slot packets are generated. It will generate $K+1$ time interval $\gamma = \{\gamma_1, \gamma_2, \cdots, \gamma_{K+1}\}$. If the time interval for collecting these K packets is equal, the average entropy of this sensor node is the smallest. The minimum value is:

$$\begin{aligned} \bar{H}_T(\gamma) = \frac{1}{K} \left[\sum_{i=1}^{K+1} \sum_{j=1}^{\gamma_i} H_T(t_j) - aM + \frac{(K+1)\, be^{-k}}{(1 - e^{-k})} \right] \\ + \frac{be^{-k}}{K(e^{-k} - 1)} (K+1) \cdot \exp\left(\frac{-k \sum_{i=1}^{K+1} \gamma_i}{K+1}\right) \end{aligned}$$

if and only if $\gamma_1 = \gamma_2 = \cdots = \gamma_{K+1}$, the above equation holds.

Proof: Only the packets generated from a sensor node is considered, so spatial entropy cannot be considered, thus only the temporal entropy is considered.

On a sensor node, consider that the time slot of the collection point is $\{\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_K\}$, and the time interval can be obtained is $\gamma_1 = \varepsilon_1$, $\gamma_{K+1} = M - \varepsilon_K$, $\gamma_k = \varepsilon_k - \varepsilon_{k-1} (2 \le k \le K)$, M is the number of time slot.

For the collection point $x_{i,j}$ in the time interval γ_1, its condition entropy is:

$$H_T(x_{i,j} \mid x_\Omega) = H_T(t_j) - \frac{1}{2} [M_T(j) + M_T(\varepsilon_1 - j + 1)]$$

In time interval γ_i, there are γ_i collection points, so the total conditional entropy of γ_i is:

$$\begin{aligned} H_T(\gamma_i) = \sum_{j=1}^{\gamma_i} H_T(t_j) \\ - \frac{1}{2} \sum_{j=1}^{\gamma_i} [M_T(j - \varepsilon_{i-1}) + M_T(\varepsilon_i - j + 1)] \end{aligned}$$

Reorganized the above formula, can get

$$H_T(\gamma_i) = \sum_{j=1}^{\gamma_1} H_T(t_j) - \sum_{j=1}^{\gamma_i} M_T(j)$$

Substituting the fitting function y into the above formula

$$H_T(\gamma_i) = \sum_{j=1}^{\gamma_i} H_T(t_j) - \sum_{j=1}^{\gamma_i} (be^{-kj} + a)$$

Rearranged the above, can get

$$H_T(\gamma_i) = \sum_{j=1}^{\gamma_i} H_T(t_j) - \gamma_i a - \sum_{j=1}^{\gamma_i} be^{-kj}$$

Using Geometric series summation formula, can get

$$H_T(\gamma_i) = \sum_{j=1}^{\gamma_i} H_T(t_j) - \gamma_i a - be^{-k} \frac{1 - e^{-\gamma_i k}}{1 - e^{-k}}$$

Then, the average entropy of a sensor node is as:

$$\begin{aligned}\bar{H}_T(\gamma) &= \frac{1}{K}\left[\sum_{i=1}^{K+1}(\sum_{j=1}^{\gamma_i} H_T(t_j) - \gamma_i a - be^{-k}\frac{1-e^{-\gamma_i k}}{1-e^{-k}})\right] \\ &= \frac{1}{K}\left[\sum_{i=1}^{K+1}\sum_{j=1}^{\gamma_i} H_T(t_j) - a\sum_{i=1}^{K+1}\gamma_i \right.\\ &\quad \left. + \frac{(K+1)\,be^{-k}}{(1-e^{-k})}\right] + \frac{be^{-k}}{K(e^{-k}-1)}\sum_{i=1}^{K+1} e^{-\gamma_i k}\end{aligned}$$

Since $\sum_{i=1}^{K+1}\gamma_i = M$, Reorganized the above, can get

$$\bar{H}_T(\gamma) = \frac{1}{K}\left[\sum_{i=1}^{K+1}\sum_{j=1}^{\gamma_i} H_T(t_j) - aM + \frac{(K+1)\,be^{-k}}{(1-e^{-k})}\right] + \frac{be^{-k}}{K(e^{-k}-1)}\sum_{i=1}^{K+1} e^{-\gamma_i k}$$

Obviously, $\frac{1}{K}\left[\sum_{i=1}^{K+1}\sum_{j=1}^{\gamma_i} H_T(t_j) - aK + \frac{(K+1)be^{-k}}{(1-e^{-k})}\right]$ is a constant. Therefore, to minimize $\bar{H}_T(\gamma)$, let $\frac{be^{-k}}{K(e^{-k}-1)}\sum_{i=1}^{K+1} e^{-\gamma_i k}$ be the smallest, according to Jensen's inequality, can get:

$$\sum_{i=1}^{K+1} e^{-\gamma_i} \geq (K+1)\cdot\exp(\frac{-k\sum_{i=1}^{K+1}\gamma_i}{K+1})$$

The equal is obtained when $e^{-\gamma_1} = e^{-\gamma_2} = \cdots = e^{-\gamma_{K+1}}$. That is, when $\bar{H}_T(\gamma)$ is the smallest, the length of time interval is equal, so when the packets are equally distributed on a sensor node, the average entropy is the smallest. ■

Theorem 1 prove that when the number of packets collected by a sensor node is constant, the collection of packets at equal time intervals minimizes the temporal entropy of the matrix, minimizes temporal entropy and minimizes the average entropy of the matrix. Therefore, when congestion occurs, only the interval at which the node generates the data packet is increased, and the interval at which the data packets are generated is equal, which can minimize the average entropy, thereby ensuring the reconstruction error in temporal.

D. CONGESTION CONTROL

In the previous, how to guarantee the minimum entropy of the matrix in temporal is considered, and also verify that the spatial entropy of the matrix is difficult to control. Therefore, the congestion control is mainly carried out in spatial.

Based on matrix completion technology, the network can tolerate a part of the data missing, that is, it can collect less data, in this way, each node can be allowed to generate packets at intervals. The longer the interval between packets is generated, the lower the ratio of data generation, and the number of generated packets will be reduced, thus mitigating the congestion of nodes. However, there are also some nodes that is non-congested, so the data generation can be appropriately reduced to increase the ratio of data generation, and the reconstruction error of the collection matrix can be reduced.

Therefore, it is need to determine whether the node is congested. The queue threshold is used to determine if the node is congested. Two thresholds are stored in each node, one congestion threshold ϑ_1 and the other is the uncongested threshold ϑ_2. Each node checks the size of data stored in its queue and the size of two thresholds at regular intervals. When the size of the storage queue exceeds the congestion threshold ϑ_1, reducing its ratio of data generation. When the size of storage queue is lower than the uncongested threshold ϑ_2, it indicates that congestion does not occur and the generated rate can be increased. Such as Algorithm 1.

Algorithm 1 Algorithm for Detecting Congestion

// q_i is the storage queue of node i.
// ϑ_1 is the storage queue congestion threshold.
// ϑ_2 is the storage queue uncongested threshold.
// ϖ is the detection interval.
1. For each node i
2. If $q_i size() \geq \vartheta_1$
3. Execute Algorithm 2
4. else If $q_i size() \leq \vartheta_2$
5. Execute Algorithm 3
6. End if
7. End for
8. let simTime = Current_time
9. Generate the next check event E.
10. The trigger time of event E is set as (simTime + ϖ).

When a node is detected as congested, its generated rate is reduced. Decreasing the generated rate reduces the number of packets collected, resulting in the average entropy of the collection matrix increased, and increasing the reconstruction error after recovery. Therefore, while the congestion node reduces the generated rate, the uncongested node can increase the generated rate appropriately. However, when the generated rate at congested node reduced too much, some nodes that are not congested may have congestion due to the generated rate increased. Therefore, the minimum generated rate that a subtree is as Theorem 2.

Theorem 2: When the subtree rooted at node i needs to generate N_i, the number of packets generated by node i is x_i, and the maximum generated rate is β. The lowest generated rate of any child nodes is:

$$\alpha_{min} = \frac{N_i - x_i - (S_i - S_j - 1)T\beta}{S_j}$$

Proof: Considering the network generates a total of T cycles of data. For a node i, the number of nodes in the subtree is S_i. Considering j is the child node of node i, node i has generated x_i packets. The maximum number of packets that can be generated by the other node is:

$$N_j^{'} = (S_i - S_j - 1)T\beta$$

Therefore, the minimum number of packets that node j needs to generate is:

$$N_j = N_i - N_j^{'} = N_i - x_i - (S_i - S_j - 1)T\beta$$

Algorithm 2 Algorithm for Congested Nodes

// α is the data generated rate saved by each node.
// Q is the number packet reduced in the subtree.
// Δ is the decrease step size of generated rate.
// p_1 is congested message.
// p_2 is the acknowledgement message from parent node.
// p_3 is the reduction message.
// p_4 is the acknowledgement message from child node.

Case 1: The congestion detected

1. Send p_1 to parent node.
2. Receive p_2 from parent node, and $p_2 -> \alpha_{min}$
3. $Q = 0$
4. If $\alpha - \Delta \geq \alpha_{min}$
5. $\alpha = \alpha - \Delta$
6. $Q = Q + \Delta T$
7. End if
8. For each child node v
9. Generate p_3, and $\alpha_{min} -> p_3$
10. Send p_3 to node v 11. Receive p_4 from node v, and $p_4 -> Q_v$
12. $Q = Q + Q_v$
13. End for
14. Generate p_4, and $Q -> p_4$
15. Send p_4 to parent node

Case 2: Received congested message from nodej

// The current node is node i

1. $\alpha_{min} = \frac{N_i - x_i - (S_i - S_j - 1)T\beta}{S_j}$
2. Generate p_2, and $\alpha_{min} -> p_2$
3. Send p_2 to node j

Case 3: Received the reduction message

11. Q=0
12. If $\alpha - \Delta \geq \alpha_{min}$
13. $\alpha = \alpha - \Delta$
14. $Q = Q + \Delta T$
15. End if
16. For each child node i
17. Generate p_3, $\alpha_{min} -> p_3$ 18. Send p_3 to node i
19. Receive p_4, and $p_4 -> Q_i$
20. $Q = Q + Q_i$
21. End for
22. Generate p_4, and $Q -> p_4$
23. Send p_4 to its parent node.

Thus, the lowest generated rate is

$$\alpha_{min} = \frac{N_i - x_i - (S_i - S_j - 1)T\beta}{S_j}$$

■

Theorem 2 gives the lowest generated rate to ensure data quality. when congestion occurs, the generated rate of the congested node is not lower than this value to ensure the quality of the recovered data. Therefore, for nodes that generate congestion, the method of mitigating congestion such as Algorithm 2.

Algorithm 3 Algorithm for Non-Congested Nodes

// α is the data generated rate saved by each node.
// Q is the number packet increased in the subtree.
// Δ is the increase step size of generated rate.
// Θ is the mark whether need to increased generated rate.
// β is the maximum generated rate.
// p_1 is the confirmation message.
// p_2 is the acknowledgement message from parent node.
// p_3 is the increased message.
// p_4 is the acknowledgement message from child node.

Case 1: The non-congestion detected

1. Send p_1 to parent node.
2. Receive p_2 from parent node, and $p_2 -> \Theta$
3. If $\Theta == true$
4. $Q = 0$
5. If $\alpha + \Delta < \beta$
6. $\alpha = \alpha + \Delta$
7. $Q = Q + \Delta T$
8. End if
9. For each child node v
10. Generate p_3
11. Send p_3 to node v
12. Receive p_4 from node v, and $p_4 -> Q_v$
13. $Q = Q + Q_v$
14. End for
15. Generate p_4, and $Q -> p_4$
16. Send p_4 to parent node
17. End if

Case 2: Received congested message from nodej

// The current node is node i

1. If Q_i>0
2. $\Theta = true$
3. else
4. $\Theta = false$
5. End if
6. Generate p_2, and $\Theta -> p_2$
7. Send p_2 to node j

Case 3: Received the reduction message

1. Q=0
2. If $\alpha + \Delta < \beta$
3. $\alpha = \alpha + \Delta$
4. $Q = Q + \Delta T$
5. End if
6. For each child node v
7. Generate p_3
8. Send p_3 to node v
9. Receive p_4, and $p_4 -> Q_v$
10. $Q = Q + Q_v$
11. End for
12. Generate p_4, and $Q -> p_4$
13. Send p_4 to its parent node.

In Algorithm 2, when a node is congested, it first sends a message to its parent node. The parent node calculates the lowest generated rate of the subtree where the node is

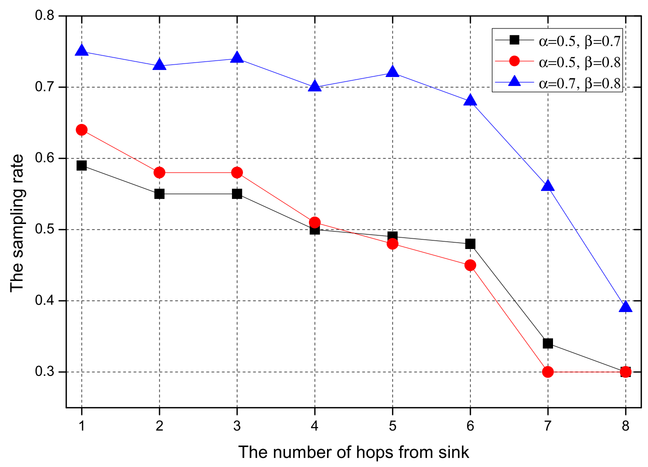


FIGURE 8. The sampling rate of each node.

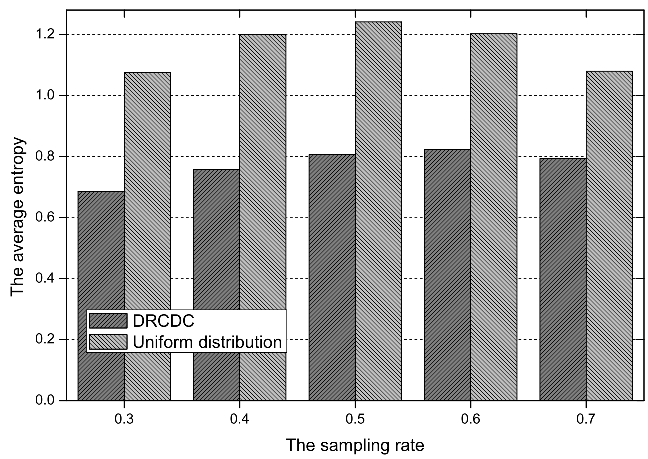


FIGURE 9. The sampling rate at different sampling rate.

congested according to Theorem 2, and sends the lowest generated rate to the congested node (The Case 2 of Algorithm 2). Then, the node that is congested begins to reduce the generated rate of the nodes in its subtree (The Case 3 of Algorithm 2). Finally, the congestion node will send the number of packets that is reduced to its parent node, and each node maintains a value to store the number of packets reduced by its subtree.

Since the nodes that are congested will reduce the number of packets generated by them, the data quality of the collected data will be affected. Therefore, for nodes that are not congested, the number of packets can be increased, such as Algorithm 3.

In Algorithm 3, when the nodes do not have congestion, and its siblings are congested, the generated rate is reduced. The current node can appropriately increase the generated rate to reduce the reconstruction error of the matrix. Therefore, the congestion of node is detected at regular intervals, and the generated rate of the node is adaptively adjusted according to the current situation of the node, and the congestion of the network is mitigated under the premise of ensuring the quality of the collected data.

Fig. 8 is the generated rate of each node after collecting 500 rounds of data under our congestion control method. In the Fig. 5, α represents the generated rate that the network needs to collect before collection. Once the node is congested, the generated rate of the entire subtree will decrease. Therefore, congestion at the node near the sink will definitely affect the generated rate of the far sink node, and the congestion of the node of the far sink will not affect the node near the sink. Therefore, the generated rate of nodes in the far sink area will be lower.

Fig. 9 is the average entropy of the matrix. It can be seen that the average entropy of the matrix generated in DRCDC is lower than the random distribution at any sampling rate. It can be obtained from the previous work; the average entropy of the matrix represents the reconstruction error of the matrix. Therefore, the DRCDC scheme is good to ensure the reconstruction error after matrix recovery.

TABLE 1. Experiment parameters.

Parameters	Value	Value
R	Network radius (m)	500
r	Sensing range (m)	100
d_0	Threshold distance (m)	87
L	The size of data packets (bit)	1024
ϑ	Channel transmission rate (bit/s)	100
ς	Transmission success rate	0.8
m	The queue size (packets)	10
E_{elec}	Transmitting circuit loss (nJ/bit)	50
ε_{fs}	Power amplification for the free space (pJ m^2/bit)	10
ε_{mp}	Power amplification for the multi-path fading (pJ m^4/bit)	0.0013
β	The maximum generate rate	0.8
ϑ_1	The congestion threshold	8
ϑ_2	The uncongested threshold	4

V. THE EXPERIMENTAL RESULTS AND ANALYSIS

The DRCDC scheme uses omnet++ [61] to carry out simulation experiments. The experimental parameters are shown in Table 1.

In the simulation experiment, the energy model used in this is the energy consumption model in [53], the node will consume energy when sending data and receiving data. The energy consumption formula is as follows:

$$E_T = \begin{cases} L\left(E_{elec} + \varepsilon_{fs} d^2\right), & d \le d_0 \\ L\left(E_{elec} + \varepsilon_{mp} d^4\right), & d > d_0 \end{cases}$$
$$E_R = LE_{elec}$$

The nodes in the network are randomly and evenly distributed in a circular with a radius of 500m. A total of 500 nodes randomly distributed in a circular network, as shown in Fig. 10.

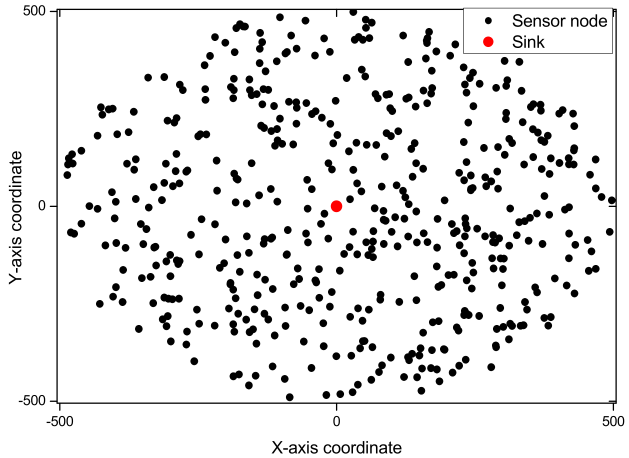


FIGURE 10. The node distribution.

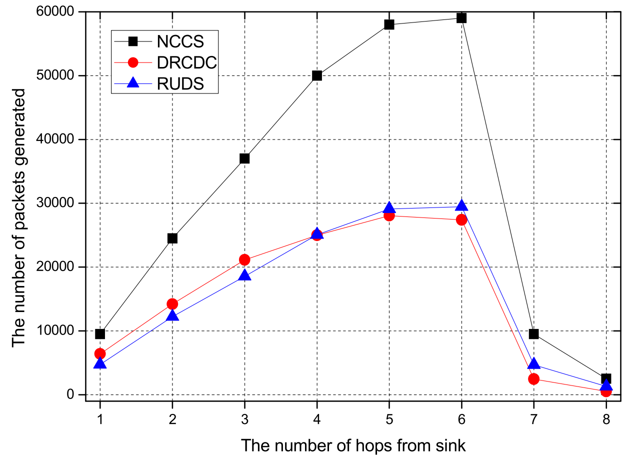


FIGURE 11. The amount of data generated by nodes.

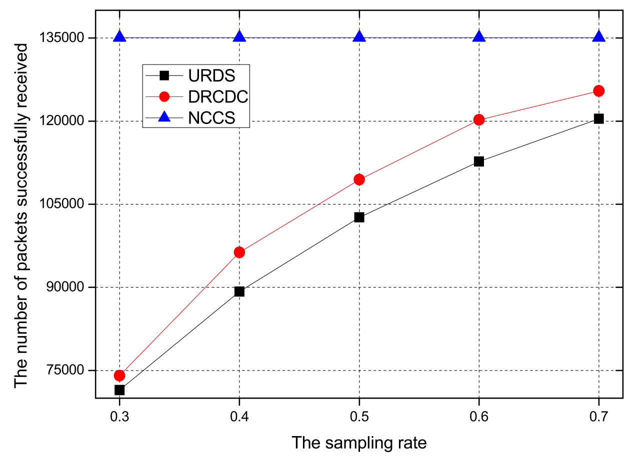


FIGURE 12. The number of packets successfully received by sink at different sampling rate.

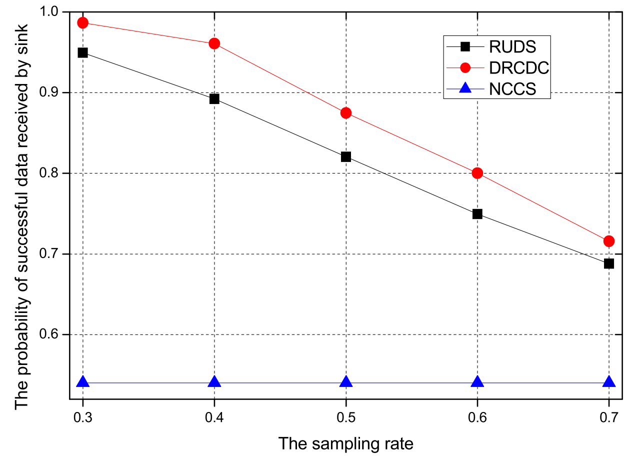


FIGURE 13. The delivery success rate at different sampling rate.

In the experiment, three schemes have tested, one is the No Congestion Control scheme (NCCS), the other is the Random uniform distribution scheme (RUDS), and the last one is our proposed DRCDC scheme.

A. DATA ESTIMATION ERROR

Since the DRCDC scheme can tolerate data loss, the estimation error of the collected data is need to be considered. In the experiment, the packets are generated by 500 cycles, and the number of packets generated by each node is shown in Fig. 11.

Fig. 11 is the number of packets generated by each node. The sampling rate used by RUDS and DRCDC is 0.5. It can be seen that NCCS does not reduce the number of packets generated by the source node. Therefore, the number of packets generated by the NCCS is significantly higher than the other two schemes. The RUDS scheme is more evenly distributed than the DRCDC scheme. The DRCDC has more packets distributed on the nodes near the sink.

Fig. 12 is the number of packets successfully received by the sink under different sampling rates. It can be seen that NCCS successfully collects the most packets, and the number of packets successfully collected by URDS and DRCDC is related to the sampling rate. The higher the sampling rate, the higher the packets collected by two schemes will increase. And the number of packets successfully collected by the DRCDC scheme is greater than that of URDS.

Fig. 13 is the success rate of data transmission at different sampling rates. Although NCCS has successfully collected the most packets, its data transmission rate is very low because it generates a lot of packets. In RUDS and DRCDC, the success rate of transmission also decreases with the increase of sampling rate, which means that increasing the number of packets generated will increase the probability of network congestion and lead to a decrease in transmission success rate. And it can be seen that the transmission success rate of DRCDC is higher than the transmission success rate of RUDS, and the number of packets generated by these two schemes is almost the same. Therefore, the DRCDC scheme is better than the RUDS scheme.

Fig. 14 is the average entropy of the collected data matrix obtained after the collection process is completed. In NCCS, the average entropy of the matrix collected in this way is not

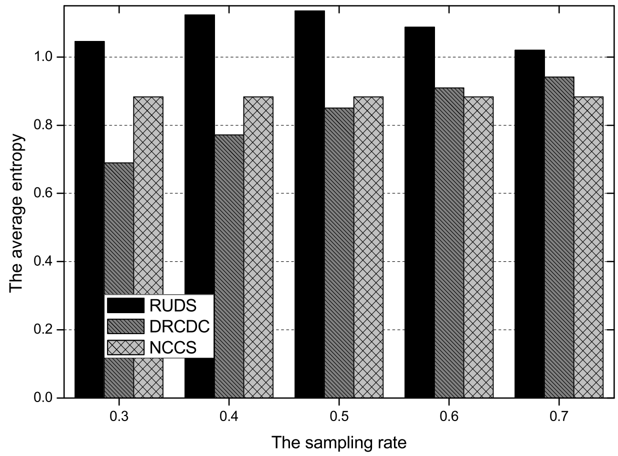


FIGURE 14. The average entropy at different sampling rate.

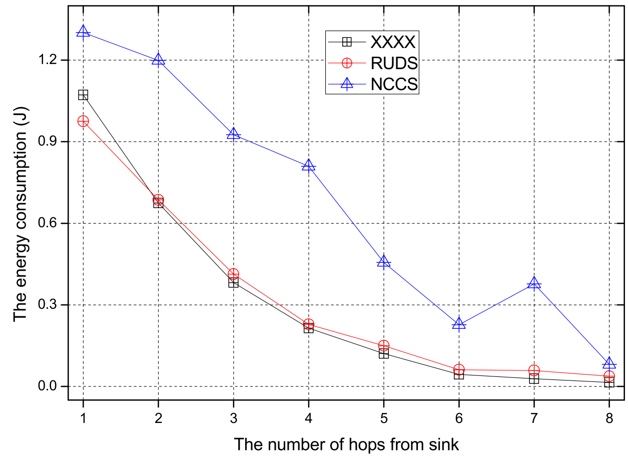


FIGURE 15. The energy consumption of each node.

0 because congestion during the collection process. It can be seen that the average entropy of the DRCDC scheme is lower than the RUDS scheme. But as the sampling rate increases, the average entropy of the DRCDC scheme will increase. Although the mutual information of two periods becomes smaller as its time interval becomes larger, the entropy of a period is not monotonous, it is a convex function. Therefore, the number of packets collected increases, which increases the probability that collection points will be collected in one cycle. The increase in the probability of being collected does not necessarily reduce the entropy of this cycle. Therefore, the average entropy of the matrix increases with the sampling rate in the DRCDC scheme. And in the RUDS scheme, it can better reflect that entropy is a convex function. In the matrix after the collection is completed, the average entropy of the DRCDC scheme is reduced by 7.74%-34% compared with the average entropy of the RUDS scheme.

B. NETWORK LIFETIME

Network lifetime is defined as the time which the first node in the network dies. Therefore, network lifetime is related to the node with the most energy consumption in the network. The nodes with the most energy consumption in the network are used to measure the network lifetime.

Fig. 15 is the energy consumption of the network at sampling rate of 0.5. It can be seen that the more hops from the sink, the smaller the energy consumption of the node in general. However, in NCCS scheme, the energy consumption of the node 7 hops away from the sink has already exceeded that of the nodes 6 hops away from the sink. This is because the large amount of congestion generated at this location. The node needs to consume energy every time it sends data, a large amount of congestion causes the nodes at this location to be retransmitted all the time, resulting in an increase in energy consumption. In the network after the congestion control is adopted, since the congestion of the network is mitigated, the energy consumption of the node is gradually reduced according to the distance from the sink.

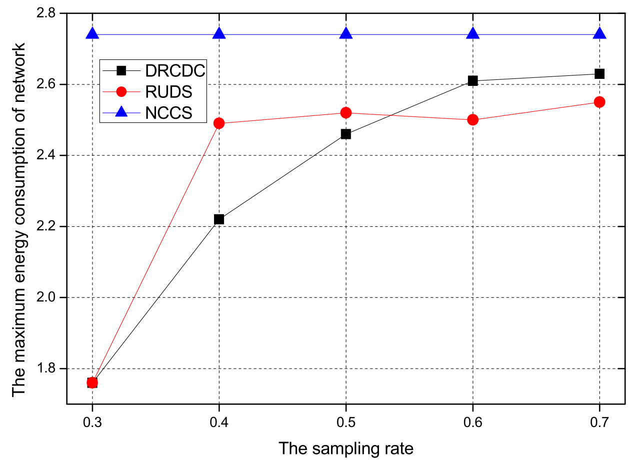


FIGURE 16. The maximum energy consumption at different sampling rate.

Fig. 16 is the maximum energy consumption of a network that collects different amounts of data. The NCCS scheme does not reduce the amount of data that need to be collected during the collection process. Therefore, its energy consumption is greater than that of DRCDC and RUDS scheme. As can be seen from the Fig. 16, in many cases, the maximum energy consumption of the proposed DRCDC scheme in the network is lower than that of the RUDS scheme. However, since the packet loss in RUDS scheme is higher than our proposed DRCDC scheme. When the network is congested, many packets cannot be transmitted to the near-sink area. Therefore, the maximum energy consumption of the RUDS scheme is lower than the DRCDC scheme in high sampling rate. Compared to the RUDS scheme, the DRCDC scheme can reduce the maximum energy consumption by $-3.1\%-10.8\%$.

C. PACKET LOSS

In the network that uses the retransmission mechanism [47] to ensure the reliability of network transmission, a maximum number of retransmissions is set. When the number of retransmissions reaches the maximum number of

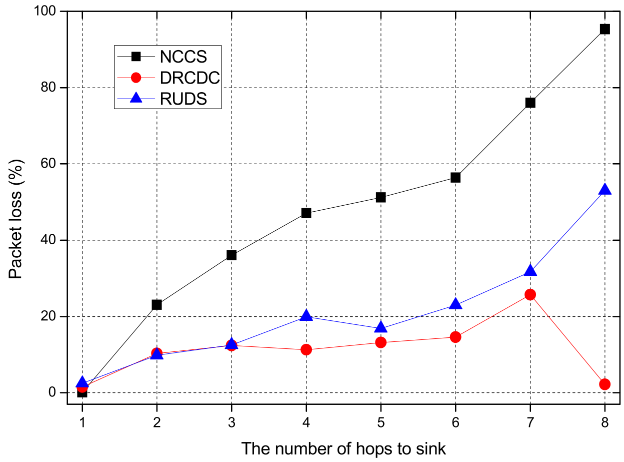


FIGURE 17. The packet loss of each node.

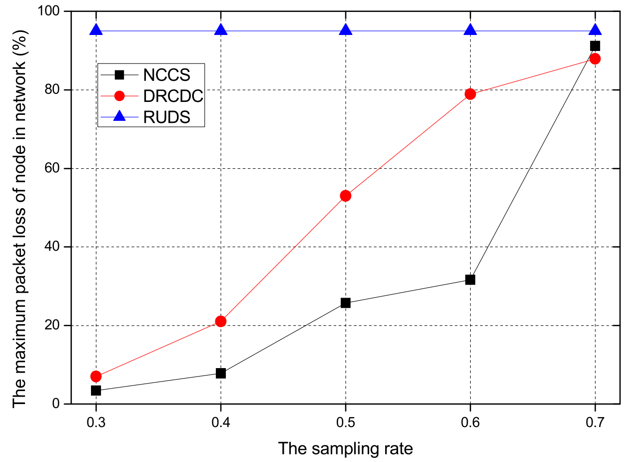


FIGURE 18. The maximum packet loss in network.

retransmissions, the next packets will be transmitted, and the current packet will be lost. In the network that is easy to congestion, because the node is congested, the storage queue is full and cannot receive data. Therefore, the upstream node will resend the packet until the maximum number of retransmissions results in packet loss. Therefore, packet loss is also an important condition for measuring network congestion.

Fig. 17 is the packet loss rate of each node in the network when the sampling rate is 0.5. It can be seen that the farther away from the sink, the greater the packet loss rate, and the DRCDC scheme is better than the other two methods. The node with the largest number of sink hops has a low packet loss rate in the DRCDC scheme, this is because the DRCDC scheme has a high probability of congestion in a subtree with large number of nodes, and the nodes that 8 hops from the sink are generally distributed in subtrees with a large number of nodes, so the packet loss rate is also low.

Fig. 18 is the highest packet loss rate of single node in network at different sampling rates. It can be seen that under the NCCS scheme, there are some nodes whose transmission success rate is extremely low, and the packet loss rate reaches 95%. Most of the data of this node is lost in the transmission process, which also leads to the average entropy increase of the collection matrix. In RUDS and DRCDC, the maximum packet loss rate is greatly optimized at low sampling rate. However, both RUDS and DRCDC scheme will increase the packet loss rate as the sampling rate of the network increases. And the DRCDC scheme has a relatively increase compared to the RUDS scheme. Therefore, the DCRDC scheme is superior to the RUDS scheme in most cases. When the sampling rate is increased from 0.6 to 0.7, the maximum packet loss rate of the DRCDC scheme has increased significantly. This is because when the sampling rate is 0.7, the total collection is too large, and the congestion cannot be effectively mitigated.

Fig. 19 is the packet loss rate of the network. It can be seen that the packet loss rate of NCCS scheme has reached 50%, that is, half of the data that needs to be collected is lost during the transmission. The packet loss rate of DRCDC and RUDS scheme increases with the increase of sampling rate. In our experiment, the packet loss rate of DRCDC scheme is reduced by 2.8% to 6.8% compared with RUDS scheme.

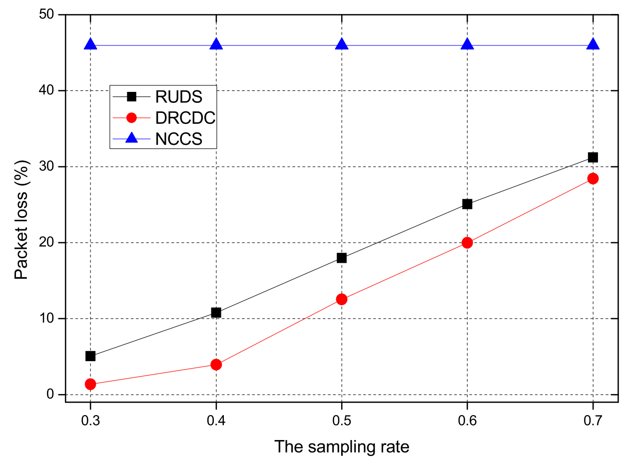


FIGURE 19. The packet loss at different sampling rate.

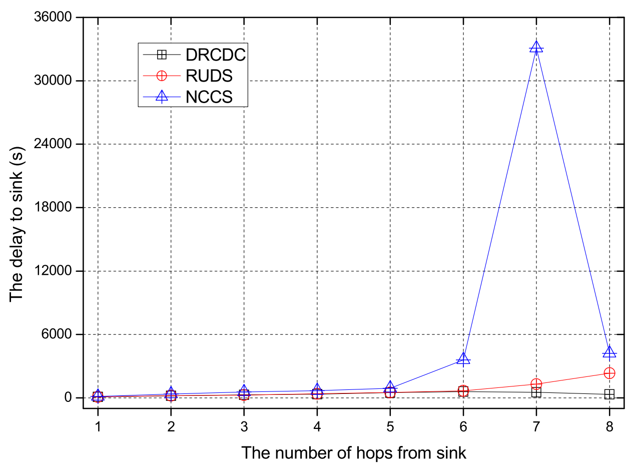


FIGURE 20. The delay of each node.

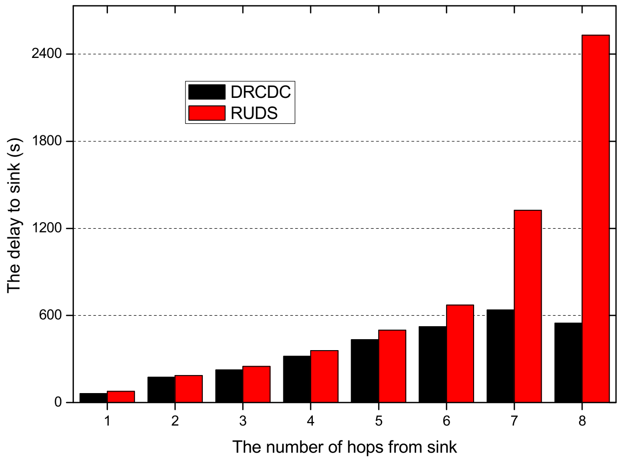


FIGURE 21. The delay of each node.

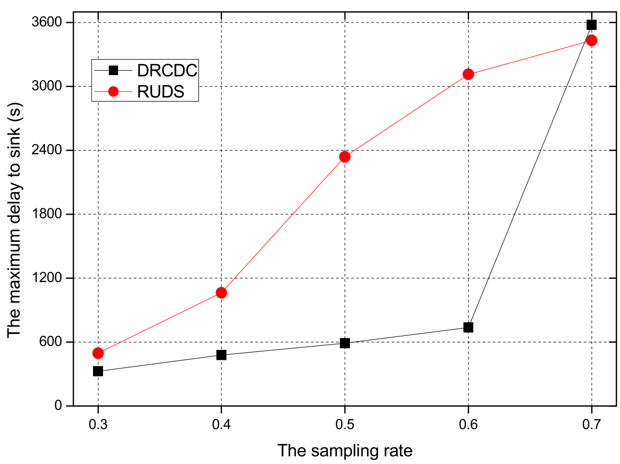


FIGURE 22. The maximum delay of network.

D. END-TO-END DELAY

End-to-end delay (also called delay) mainly refers to the time elapsed from the generation of the data packet to the successful receipt of the data packet by the target node. The delay considered in this paper is mainly the delay of data transmission. The delay of data transmission mainly consists of the following two parts: (1) In the process of transmission, the packet is lost, and the retransmission delay is generated. (2) The time the packet is waiting to be sent in the send queue, waiting for transmission.

Fig. 20 is the delay of successful transmission to sink in the case of sampling rate of 0.5. As can be seen from the Fig. 20, In NCCS scheme, it is obvious that the network has experienced severe congestion, and the transmission delay of the 7^{th} hop node is greater than the delay of the 8^{th} hop node. This is because severe congestion occurs in the transmission where the 7^{th} hop node is located, and the packet needs to wait in the node for a long time before it can be sent.

Fig. 21 is the delay of successful transmission to sink in DRCDC and RUDS scheme when the sampling rate is 0.5. In this case, the transmission delay of the DRCDC scheme is better than the RUDS scheme. Therefore, the performance of the DRCDC scheme for network congestion mitigation is better than the RUDS scheme.

Fig. 22 is the maximum delay of different sampling rate. It can be seen that the maximum delay of the network increases as the sample rate increases. When the sampling rate is 0.7, the DRCDC scheme began to experience severe congestion, and the RUDS scheme began to experience severe congestion at a sampling rate of 0.5. Therefore, the network using DRCDC scheme can collect more packets. When the sampling rate does not exceed 0.6, the DRCDC scheme reduces the delay by 34.2% to 76.3% compared to the RUDS scheme.

VI. CONCLUSION

In this paper, we propose a differentiated data collection scheme to mitigate the congestion in wireless sensor networks, while guarantees the quality of collected data. Different from the previous scheme, the DRCDC scheme avoids or mitigates congestion in both temporal and spatial based information entropy theory. In temporal, the data is collected at equal intervals, so that the temporal entropy of each sensor node is minimized, thereby reducing the average entropy of the matrix, and ensuring the quality of the collected data. In spatial, reducing the generated rate of the congestion nodes, and appropriately increase the generated rate of the uncongested node, so the generated rate is adaptively adjusted according to the environment in which each node is located, thereby congestion has been better mitigated. At the same time, the data quality can be well guaranteed because it increases the generated rate of uncongested nodes. Therefore, the DRCDC scheme is significant for research in the field of congestion control.

REFERENCES

[1] Z. Li, J. Gui, N. Xiong, and Z. Zeng, "Energy-efficient resource sharing scheme with out-band D2D relay-aided communications in C-RAN-based underlay cellular networks," *IEEE Access*, vol. 7, pp. 19125–19142, 2019. doi: 10.1109/ACCESS.2019.2891670.

[2] H. Xiong, H. Zhang, and J. Sun, "Attribute-based privacy-preserving data sharing for dynamic groups in cloud computing," *IEEE Syst. J.*, to be published. doi: 10.1109/JSYST.2018.2865221.

[3] Q. Li, A. Liu, T. Wang, M. Xie, and N. Xiong, "Pipeline slot based fast rerouting scheme for delay optimization in duty cycle based M2M communications," *Peer-Peer Netw. Appl.*, to be published. doi: 10.1007/s12083-019-00753-z.

[4] J. Li *et al.*, "Battery-friendly based relay selection scheme to prolong lifetime for sensor nodes in Internet of Things," *IEEE Access*, vol. 7, pp. 33180–33201, 2019.

[5] T. Wang, G. Zhang, A. Liu, M. Z. A. Bhuiyan, and Q. Jin, "A secure IoT service architecture with an efficient balance dynamics based on cloud and edge computing," *IEEE Internet Things J.*, to be published. doi: 10.1109/JIOT.2018.2870288.

[6] W. Zhang *et al.*, "Adaption resizing communication buffer to maximize lifetime and reduce delay for WVSNs," *IEEE Access*, vol. 7, pp. 48266–48287, 2019.

[7] Z. Li, Y. Liu, A. Liu, S. Wang, and H. Liu, "Minimizing convergecast time and energy consumption in green Internet of Things," *IEEE Trans. Emerg. Topics Comput.*, to be published. doi: 10.1109/TETC.2018.2844282.

[8] G. Gui, H. Huang, Y. Song, and H. Sari, "Deep learning for an effective nonorthogonal multiple access scheme," *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 8440–8450, Sep. 2018.

[9] L. Hu, A. Liu, M. Xie, and T. Wang, "UAVs joint vehicles as data mules for fast codes dissemination for edge networking in smart city," *Peer-Peer Netw. Appl.*, to be published. doi: 10.1007/s12083-019-00752-0.
[10] Z. Kuang, L. Li, J. Gao, L. Zhao, and A. Liu, "Partial offloading scheduling and power allocation for mobile edge computing systems," *IEEE Internet Things J.*, to be published. doi: 10.1109/JIOT.2019.2911455.
[11] X. Deng, T. He, L. He, J. Gui, and Q. Peng, "Performance analysis for IEEE 802.11 s wireless mesh network in smart grid," *Wireless Pers. Commun.*, vol. 96, no. 1, pp. 1537–1555, Sep. 2017.
[12] M. Chen, Y. Li, X. Luo, W. Wang, L. Wang, and W. Zhao, "A novel human activity recognition scheme for smart health using multilayer extreme learning machine," *IEEE Internet Things J.*, to be published. doi: 10.1109/JIOT.2018.2856241.
[13] M. Luo, K. Wang, Z. Cai, A. Liu, Y. Li, and C. Cheang, "Using imbalanced triangle synthetic data for machine learning anomaly detection," *Comput., Mater. Continua*, vol. 58, no. 1, pp. 15–26, 2019.
[14] S. Zhang, K.-K. R. Choo, Q. Liu, and G. Wang, "Enhancing privacy through uniform grid and caching in location-based services," *Future Gener. Comput. Syst.*, vol. 86, pp. 881–892, Sep. 2018.
[15] S. Zhang, X. Li, Z. Tan, T. Peng, and G. Wang, "A caching and spatial K-anonymity driven privacy enhancement scheme in continuous location-based services," *Future Gener. Comput. Syst.*, vol. 94, pp. 40–50, May 2019.
[16] N. Zhao *et al.*, "Secure transmission for interference networks: User selection and transceiver design," *IEEE Syst. J.*, to be published. doi: 10.1109/JSYST.2019.2891641.
[17] S. Sarkar, S. Chatterjee, and S. Misra, "Assessment of the suitability of fog computing in the context of Internet of Things," *IEEE Trans. Cloud Comput.*, vol. 6, no. 1, pp. 46–59, Mar. 2018.
[18] J. Ren, Y. Zhang, R. Deng, N. Zhang, D. Zhang, and X. Shen, "Joint channel access and sampling rate control in energy harvesting cognitive radio sensor networks," *IEEE Trans. Emerg. Topics Comput.*, vol. 7, no. 1, pp. 149–161, Jan./Mar. 2019. doi: 10.1109/TETC.2016.2555806.
[19] L. Yin, J. Gui, and Z. Zeng, "Improving energy efficiency of multimedia content dissemination by adaptive clustering and D2D multicast," *Mobile Inf. Syst.*, vol. 2019, Mar. 2019, Art. no. 5298508. doi: 10.1155/2019/5298508.
[20] F. Wang *et al.*, "To reduce delay, energy consumption and collision through optimization duty-cycle and size of forwarding node set in WSNs," *IEEE Access*, vol. 7, pp. 55983–56015, 2019. doi: 10.1109/ACCESS.2019.2913885.
[21] Z. Liu, T. Tsuda, H. Watanabe, S. Ryuo, and N. Iwasawa, "Data driven cyber-physical system for landslide detection," *Mobile Netw. Appl.*, pp. 1–12, Mar. 2018. doi: 10.1007/s11036-018-1031-1.
[22] H. Teng, W. Liu, T. Wang, A. Liu, X. Liu, and S. Zhang, "A cost-efficient greedy code dissemination scheme through vehicle to sensing devices (V2SD) communication in smart city," *IEEE Access*, vol. 7, pp. 16675–16694, 2019.
[23] Y. Ren, W. Liu, T. Wang, X. Li, N. N. Xiong, and A. Liu, "A collaboration platform for effective task and data reporter selection in crowdsourcing network," *IEEE Access*, vol. 7, pp. 19238–19257, 2019.
[24] H. Teng *et al.*, "A novel code data dissemination scheme for Internet of Things through mobile vehicle of smart cities," *Future Gener. Comput. Syst.*, vol. 94, pp. 351–367, May 2019.
[25] Y. Liu, A. Liu, N. Zhang, X. Liu, M. Ma, and Y. Hu. "DDC: Dynamic duty cycle for improving delay and energy efficiency in wireless sensor networks," *J. Netw. Comput. Appl.*, vol. 131, pp. 16–27, Apr. 2019.
[26] T. Li, K. Ota, T. Wang, X. Li, Z. Cai, and A. Liu, "Optimizing the coverage via the UAVs with lower costs for information-centric Internet of Things," *IEEE Access*, vol. 7, pp. 15292–15309, 2019.
[27] X. Liu, Y. Liu, N. Zhang, W. Wu, and A. Liu, "Optimizing trajectory of unmanned aerial vehicles for efficient data acquisition: A matrix completion approach," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1829–1840, Apr. 2019. doi: 10.1109/JIOT.2019.2894257.
[28] X. Deng, G. Li, M. Dong, and K. Ota, "Finding overlapping communities based on Markov chain and link clustering," *Peer-Peer Netw. Appl.*, vol. 10, no. 2, pp. 411–420, 2017.
[29] X. Kui, Y. Sun, S. Zhang, and Y. Li, "Characterizing the capability of vehicular fog computing in large-scale urban environment," *Mobile Netw. Appl.*, vol. 23, no. 4, pp. 1050–1067, 2018.
[30] B. Lyu, Z. Yang, H. Guo, F. Tian, and G. Gui, "Relay cooperation enhanced backscatter communication for Internet-of-Things," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 2860–2871, Apr. 2019. doi: 10.1109/JIOT.2018.2875719.
[31] Y. Liu, A. Liu, N. N. Xiong, T. Wang, and W. Gui, "Content propagation for content-centric networking systems from location-based social networks," *IEEE Trans. Syst., Man, Cybern., Syst.*, to be published. doi: 10.1109/TSMC.2019.2898982.
[32] C. Zhang, Y. Lin, L. Zhu, A. Liu, Z. Zhang, and F. Huang, "CNN-VWII: An efficient approach for large-scale video retrieval by image queries," *Pattern Recognit. Lett.*, vol. 123, pp. 82–88, May 2019.
[33] Q. Deng *et al.*, "Compressed sensing for image reconstruction via back-off and rectification of greedy algorithm," *Signal Process.*, vol. 157, pp. 280–287, Apr. 2019.
[34] G. Gui, T. Zhang, J. Dan, and L. Xu, "Stable adaptive channel estimation method under impulsive noise environments," *Int. J. Commun. Syst.*, vol. 30, no. 6, 2017, Art. no. e3104.
[35] W. Qi *et al.*, "Minimizing delay and transmission times with long lifetime in code dissemination scheme for high loss ratio and low duty cycle wireless sensor networks," *Sensors*, vol. 18, no. 10, p. 3516, 2018. doi: 10.3390/s18103516.
[36] X. Xiang, W. Liu, A. Liu, N. N. Xiong, Z. Zeng, and Z. Cai, "Adaptive duty cycle control–based opportunistic routing scheme to reduce delay in cyber physical systems," *Int. J. Distrib. Sensor Networks.*, vol. 15, no. 4, Apr. 2019. doi: 10.1177/1550147719841870.
[37] Y. Liu, M. Ma, X. Liu, N. Xiong, A. Liu, and Y. Zhu, "Design and analysis of probing route to defense sink-hole attacks for Internet of Things security," *IEEE Trans. Netw. Sci. Eng.*, to be published. doi: 10.1109/TNSE.2018.2881152.
[38] J. Gui and K. Zhou, "Flexible adjustments between energy and capacity for topology control in heterogeneous wireless multi-hop networks," *J. Netw. Syst. Manage.*, vol. 24, no. 4, pp. 789–812, 2016.
[39] J. Gui, M. Ahmadi, and F. Tong, "Dynamically constructing and maintaining virtual access points in a macro cell with selfish nodes," *J. Syst. Softw.*, vol. 108, pp. 1–22, Oct. 2015.
[40] T. Wang, G. Zhang, M. Z. A. Bhuiyan, A. Liu, W. Jia, and M. Xie, "A novel trust mechanism based on fog computing in sensor–cloud system," *Future Gener. Comput. Syst.*, to be published. doi: 10.1016/j.future.2018.05.049.
[41] B. Huang, W. Liu, T. Wang, X. Li, H. Song, and A. Liu, "Deployment optimization of data centers in vehicular networks," *IEEE Access*, vol. 7, pp. 20644–20663, 2019. doi: 10.1109/ACCESS.2019.2897615.
[42] Y. Sankarasubramaniam, Ö. B. Akan, and I. F. Akyildiz, "ESRT: Event-to-sink reliable transport in wireless sensor networks," in *Proc. 4th ACM Int. Symp. Mobile Ad Hoc Netw. Comput.*, 2003, pp. 177–188.
[43] C. J. Raman and V. James, "FCC: Fast congestion control scheme for wireless sensor networks using hybrid optimal routing algorithm," *Cluster Comput.*, pp. 1–11, Jan. 2018. doi: 10.1007/s10586-018-1744-8.
[44] R. Du, C. Chen, B. Yang, N. Lu, X. Guan, and X. Shen, "Effective urban traffic monitoring by vehicular sensor networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 1, pp. 273–286, Jan. 2015.
[45] W.-W. Fang, J.-M. Chen, L. Shu, T.-S. Chu, and D.-P. Qian, "Congestion avoidance, detection and alleviation in wireless sensor networks," *J. Zhejiang Univ. Sci. C*, vol. 11, no. 1, p. 63, 2010.
[46] J. Tan *et al.*, "An adaptive collection scheme-based matrix completion for data gathering in energy-harvesting wireless sensor networks," *IEEE Access*, vol. 7, pp. 6703–6723, 2019.
[47] Y. Liu, A. Liu, X. Liu, and X. Huang, "A statistical approach to participant selection in location-based social networks for offline event marketing," *Inf. Sci.*, vol. 480, pp. 90–108, Apr. 2019.
[48] X. Xiang, W. Liu, N. N. Xiong, H. Song, A. Liu, and T. Wang, "Duty cycle adaptive adjustment based device to device (D2D) communication scheme for WSNs," *IEEE Access*, vol. 6, pp. 76339–76373, 2018.
[49] J.-W. Xu, K. Ota, M.-X. Dong, A.-F. Liu, and Q. Li, "SIoTFog: Byzantine-resilient IoT fog networking," *Frontiers Inf. Technol. Electron. Eng.*, vol. 19, no. 12, pp. 1546–1557, 2018.
[50] M. Huang, W. Liu, T. Wang, H. Song, X. Li, and A. Liu, "A queuing delay utilization scheme for on-path service aggregation in services-oriented computing networks," *IEEE Access*, vol. 7, pp. 23816–23833, 2019. doi: 10.1109/ACCESS.2019.2899402.
[51] J. Paek and R. Govindan, "RCRT: Rate-controlled reliable transport for wireless sensor networks," in *Proc. 5th Int. Conf. Embedded Netw. Sensor Syst.*, 2007, pp. 305–319.
[52] L. Q. Tao and F. Q. Yu, "ECODA: Enhanced congestion detection and avoidance for multiple class of traffic in sensor networks," *IEEE Trans. Consum. Electron.*, vol. 56, no. 3, pp. 1387–1394, Aug. 2010.
[53] S. Sheikh, R. Wolhuter, and H. A. Engelbrecht, "An adaptive congestion control and fairness scheduling strategy for wireless mesh networks," in *Proc. IEEE Symp. Ser. Comput. Intell.*, Dec. 2015, pp. 1174–1181.

[54] H. Ahmadi and T. Abdelzaher, "An adaptive-reliability cyber-physical transport protocol for spatio-temporal data," in *Proc. 30th IEEE Real-Time Syst. Symp.*, Dec. 2009, pp. 238–247.
[55] Y. Zhuang *et al.*, "Data collection with accuracy-aware congestion control in sensor networks," *IEEE Trans. Mobile Comput.*, vol. 18, no. 5, pp. 1068–1082, May 2019. doi: 10.1109/TMC.2018.2853159.
[56] K. Xie, L. Wang, X. Wang, G. Xie, and J. Wen, "Low cost and high accuracy data gathering in WSNs with matrix completion," *IEEE Trans. Mobile Comput.*, vol. 17, no. 7, pp. 1595–1608, Jul. 2018.
[57] J. Cheng, Q. Ye, H. Jiang, D. Wang, and C. Wang, "STCDG: An efficient data gathering algorithm based on matrix completion for wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 850–861, Feb. 2013.
[58] J. F. Cai, E. J. Candès, and Z. Shen, "A singular value thresholding algorithm for matrix completion," *SIAM J. Optim.*, vol. 20, no. 4, pp. 1956–1982, 2010.
[59] S. Madden. (2004). *Intel Lab Data*. [Online]. Available: http://db.csail.mit.edu/labdata/labdata.html
[60] *OriginPro*. Accessed: Feb. 1, 2019. [Online]. Available: https://www.originlab.com/Origin
[61] *Omnet++ Network Simulator, Version 5.4.1*. Accessed: Feb. 1, 2019. [Online]. Available: https://omnetpp.org/software/2018/06/29/omnet-5-4-1-released.html

JIAWEI TAN is currently pursuing the master's degree with the School of Computer Science and Engineering, Central South University, China. His research interests include data process, crowd sensing networks, and wireless sensor networks.

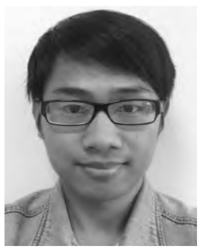
WEI LIU received the Ph.D. degree in computer application technology from Central South University, China, in 2014. He is currently an Associate Professor and a Senior Engineer with the School of Informatics, Hunan University of Chinese Medicine, China. His research interests include software engineering, data mining and medical informatics. He has published more than 20 papers in the related fields.

TIAN WANG received the B.Sc. and M.Sc. degrees in computer science from Huaqiao University, in 2004 and 2007, respectively, and the Ph.D. degree from the City University of Hong Kong, in 2011. He is currently an Associate Professor with the National Huaqiao University of China. His research interests include wireless sensor networks, social networks, and mobile computing.

SHAOBO ZHANG received the B.Sc. and M.Sc. degrees in computer science from the Hunan University of Science and Technology, Xiangtan, China, in 2003 and 2009, respectively, and the Ph.D. degree in computer science from Central South University, Changsha, China, in 2017. He is currently a Lecturer with the School of Computer Science and Engineering, Hunan University of Science and Technology. His research interest includes privacy and security issues in social networks and cloud computing.

ANFENG LIU received the M.Sc. and Ph.D. degrees in computer science from Central South University, China, in 2002 and 2005, respectively. He is currently a Professor with the School of Computer Science and Engineering, Central South University, China. His current research interest includes wireless sensor networks. He is also a member of the China Computer Federation (CCF).

MANDE XIE was born in 1977. He received the Ph.D. degree in circuit & system from Zhejiang University, in 2006. He is currently a Professor with Zhejiang Gongshang University. His research interests include wireless sensor networks (WSNs), social networks, and privacy preservation.



MING MA is currently pursuing the Ph.D. degree with the Department of Computer Science, Stony Brook University, USA. His research interests include geometric modeling, digital geometric processing, and wireless sensor networks.

MING ZHAO received M.Sc. and Ph.D. degrees in computer science from Central South University, China, in 2003 and 2007, respectively. He is currently a Professor with the School of Software, Central South University, China. His current research interest includes wireless networks. He is also a Member of the China Computer Federation (CCF).