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Research Article

Congestion Control Based on Consensus in the Wireless Sensor Network

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The congestion control algorithm based on the weighted directed graph is designed for the network congestion over the wireless sensor network. The congestion problem is modeled as a distributed dynamic system with time-varying delay, and it can be proven that the sent rate for all nodes converges to the available bandwidth of the sink by the proposed congestion control algorithm. Via Lyapunov function, the validity of the proposed algorithm is shown under the varying network topologies. Ns simulation results indicate that the proposed algorithm restrains the congestion over the wireless sensor network, maintains a high throughput and a low delay time, and also improves the quality of service for the whole network.

1. Introduction

Over the last decades, there have been widely researches in the area of the wireless sensor networks (WSNs) [1]. WSNs are being deployed for several mission-critical tasks, such as habitat monitoring [2], structural health monitoring [3, 4], image sensing [5], and physical game [6]. Typically, a sensor network may contain thousands of nodes, which are cheap, and small size sensors; otherwise, in many applications, the sensor nodes will be deployed in the remote area, such as the high mountain area, and the satellite in the outer space, in which case recharging is not feasible. Thus, the main focus for WSNs is on the low energy use within the autonomous, cooperative nodes which may be constrained in terms of a small memory and a low computing capability.

A wireless sensor network consists of the distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion, or pollutants. The physical parameters and the information of the interactions, in conjunction with the variable wireless network conditions, may result in unpredictable behavior in terms of the traffic load variations and the link capacity fluctuations [7]. The network condition is worsened by link bit errors [8], medium contention [9], or potential handoff operations in wireless networks. These hostile factors are likely to occur in WSN environments, thus increasing the possibility of congestion. In data networking and queuing theory, network congestion occurs when a link or node is carrying so much data that its quality of service deteriorates. In the context of WSNs, data is passed using multihop routes between sensors until they reached the sink, so the convergent (many-to-one) nature of WSN, especially in single-sink WSNs, increases the susceptibility to congestion. When a network is congested, it has settled into a stable state where the traffic demand is high, but little useful throughput is available. The high levels of the time delay and packet loss caused by congestion may deteriorate the quality of service (QoS). Especially, packet loss may activate the time-out retransmission scheme of TCP, and the retransmitted packet may worsen the congestion and even cause more retransmission request. The vicious circle may consume more energy in the retransmitted packet repeatedly and ineffectively. Consequently, congestion in WSN causes radical decrease in the delivery ratio and an increase in per-packet energy consumption.

The resource limited and unpredictable characteristics of WSNs necessitate decentralized, robust, self-adaptive, and scalable mechanisms [7]. The novel congestion control for WSNs should be simple to implement at an individual node level with minimal energy usage. Queue-based congestion control schemes and rate-based ones are the most popular congestion control schemes to solve the congestion problem. The drawback [10] of the queue-based schemes is that a backlog is inherently necessitated; on the other hand, the rate-based schemes [11] can provide early feedback for congestion. So the rate-based scheme is chosen in this paper to solve the congestion problem for WSNs. As the wireless nodes can self-organize into a wireless sensor network, in this architecture, the wireless sensor network is considered as a distributed dynamic system. Natural designs have inherent powerful characteristics and are often more effective and simpler than man-made designs [12]. And the consensus analysis of the complex network theory, such as fish swarming and bird flocking, is used in our paper. With the help of the graph theory, a congestion control algorithm based on consensus analysis (CC-CA) is proposed in this paper, considering the sink as a leader. Ns simulation results indicate that our CC-CA could restrain the congestion over wireless sensor network and maintain a high throughput and a low delay time. It can also improve the QoS for the whole network. As can be seen from the conclusion, CC-CA designed for WSN is superior from throughput, drop ratio, and average delay time of the conventional congestion control.

The rest of the paper is structured as follows: Section 2 presents the previous works on congestion control for WSNs. Section 3 presents the congestion model based on the graph theory for WSN. In Section 4, the theoretical results for congestion control algorithm based on a leader are provided. Section 5 contains a performance evaluation of the proposed scheme and a comparison with TCP protocol. The conclusion of this paper is presented in Section 6.

2. Related Works

The conventional congestion control algorithms are almost end-to-end schemes [14], which follow the TCP's end-to-end mechanism. A centralized congestion control (CC) approach cannot be generally applied since it provokes several serious drawbacks [15]. Firstly, such approach leads to excessive communication load in the network which rapidly depletes the batteries [1]. Secondly, the time-varying nature of the radio channel and the asymmetry in communication links make it harder for even regulated traffic to reach the sink [16]. Thirdly, hop-to-hop schemes [17, 18] could result in a better performance and a faster reaction than the end-to-end mechanisms. Finally, WSNs permit simple processing and a decision making by individual nodes [19] rather than a centralized approach.

Early studies in the area of the sensor networks were mostly focused on fundamental networking problems, for example, topology [20], routing [21], and energy efficiency [22], largely ignoring network performance assurances.

As the queue length in buffer suggested the current network condition, fusion [23] is a congestion mitigation technique that uses queue lengths to detect the congestion. Three different techniques have been adopted to alleviate the congestion in fusion, which included hop-by-hop flow control, rate limiting, and a prioritized MAC. IFRC [24] is a distributed rate allocation scheme that uses queue sizes to detect the congestion and further shares the congestion state through overhearing.

Rate-based congestion control may react more rapidly than queue-based scheme, so a large number of congestion control based on data rate emerges in WSNs. The bandwidth for the sensor node in ARC [25] is split proportionally between route-through and locally generated traffic, by estimating the number of upstream nodes. Congestion control and fairness for many-to-one routing in sensor networks [13] is another rate assignment scheme that uses a different congestion detection mechanism from IFRC.

QoS technique is also widely used in congestion control of the wireless sensor networks. In [26] a dual-path QoS routing protocol is designed to increase the network lifetime and reduce packet delay. MQOSR [27] is another QoS-enabled multipath routing protocol, assuming that the base stations are typically many orders of magnitude more powerful than sensor nodes. Global positioning systemss (GPS) [28, 29], which is providing the location information, is used to discover the congestion regions, while GPS receivers are expensive and not suitable in the construction of the small cheap sensor nodes.

3. Congestion Model Description

The self-organization and multihop characteristic of the WSNs indicate that the wireless sensor network is modeled as a distributed dynamic system based on the directed graph theory. The sink is considered as a "leader" node, in which the mass of information is gathered and computed. We consider that $G = (V, E, \mathbf{A})$ is a weighted directed graph with $n + 1$ nodes, where V denotes the set of vertices v_i $(i \in \mathscr{L} = \{0, 1, 2, \ldots, n\})$, E denotes the set of edges $e_{ij} = (i, j)$, $i, j \in \mathscr{L}$ of the graph G, and $\mathbf{A} = [a_{ij}] \in R^{n\times n}$ for $1, 2, \ldots, n$ is a weighted adjacency matrix.

This paper considers that the vertex indexed by 0 is assigned as the "leader," which is the sink in WSN. The other vertices of the graph G indexed by $1, 2, \ldots, n$ are referred to as "follower agents," which are the autonomous sensor nodes in WSN. When there is data transmission between v_i and v_j, then we consider that there is a path between the two nodes; otherwise $e_{ij} \notin E$. Define the weight matrix $\mathbf{A}$ for the graph G as follows:

$$a_{ij} = \begin{cases} 0.5 & e_{ij} \in E, \\ 0 & e_{ij} \notin E, \end{cases} \tag{1}$$

where $x_i \in R (i \in \mathscr{L})$ is denoted as the data bulk sent to node I, then the differential of x_i denotes the data sent rate. If there is no data communication between node i and others, $x_i = 0$. $G_x = (V, E, \mathbf{A}, x)$ with $x = (x_1, \ldots, x_n)^T$ is referred to an algebraic graph, and then we can say that the algebraic graph $G_x = (V, E, \mathbf{A}, x)$ denotes the WMN's topology.

To study a leader-following problem, the connection weight between nodes i and the leader, denoted by b_i, is shown as follows. The sink, as the last hop in the monitor area of WSN, is assigned with the largest weight:

$$b_i = \begin{cases} 0.75 & v_i \text{ connected to the leader } v_0, \\ 0 & \text{otherwise.} \end{cases} \quad (2)$$

In WSN, the sensor may begin to transmit packet suddenly or perform the backoff algorithm due to mutual interference. Namely, for the weighted directed graph $\mathbf{G}$ under consideration, the relationships between neighbors (and the interconnection topology) change over time. Define $\overline{G} = \{\overline{G}_1, \overline{G}_2, \ldots, \overline{G}_N\}$ as a set of the graphs with all possible topologies, which includes all possible interconnection graphs (involving n nodes and a leader), and denote by $S = \{1, 2, \ldots, N\}$ its index set. To describe the variable interconnection topology, we define a switching signal $\varepsilon(t) : [0, \infty) \rightarrow S$, which is piecewise constant. Therefore, the connection weights a_{ij} and b_i are time varying, and, moreover, Laplacian $\mathbf{L}_s$ $(s \in S)$ associated with the switching interconnection graph is also time varying (switched at t_i, $i = 0, 1, \ldots$).

Remark 1. The topology of WSN is time varying. And this topology is considered unchanged in any interval $[t_i, t_{i+1})$, which is reasonable for the wireless sensor network in this paper. As the network condition is not very bad, the topology of the event-driven network should remain unchanged during a data packet transmitting from one router to another. In other words, if the interval $[t_i, t_{i+1})$ approximates the propagation delay in the network, the topology will remain unchanged.

4. Congestion Control Based on the Consensus Analysis

It is indicated in [30] that, when the offered load exceeds the available capacity in the link, the packet will accumulate in the router buffer, which will induce the congestion. The congestion can be avoided, if the data bulk exchange of all nodes for one task converges to the same equilibrium point in the network. Then the congestion control problem can be attributed to the consensus problem of the complex network. Furthermore, in our simulation, all the nodes are considered the same as each other, and they split the bandwidth fairly.

Here, the entire considered data rate accelerates in a rule:

$$\begin{aligned} \dot{x}_i &= v_i, \\ \dot{v}_i &= \sum_{j \in N_i(t)} a_{ij}(t) \left(x_i(t-r) - x_j(t-r) \right) \\ &\quad + b_i(t) \left(x_0(t-r) - x_i(t-r) \right) + k \left(v_0 - v_i(t) \right), \end{aligned} \quad (3)$$

where N_i is the set of neighbors of node i $(i \in \mathscr{L})$, which is denoted by $N_i = \{v_j \in V : (i, j) \in E_r\}$ and the time-varying delay $r(t) > 0$ is a stochastic function with upper bound τ, which can be determined by the retransmission timeout in TCP.

Formula (3) can be written in a matrix form during the interval $[t_i, t_{i+1})$:

$$\begin{aligned} \dot{x}_i &= v_i, \\ \dot{v}_i &= -\left(\mathbf{L_s} + \mathbf{B_s} \right) x(t-r) - k \left(v - \mathbf{1} \otimes v_0 \right) \\ &\quad + \mathbf{B_s} \mathbf{1} \otimes x_0(t-r), \end{aligned} \quad (4)$$

where $\mathbf{L_s}$ is Laplacian of G_s, $\mathbf{B_s}$ is the leader adjacency matrix whose ith diagonal element is $b_i(t)$, and $\mathbf{1} = [1, 1, \ldots, 1]^T$.

Lemma 2. *Let G be a graph on n vertices with Laplacian $\mathbf{L}$. Denote the eigenvalues of $\mathbf{L}$ by $\lambda_1(\mathbf{L}), \ldots, \lambda_n(\mathbf{L})$; then $\lambda_1(\mathbf{L}) = 0$, and $\mathbf{1} = [1, 1, \ldots, 1]^T$ is its eigenvector.*

Lemma 2 was obtained in [31].

Denote $\tilde{x} = x - \mathbf{1} \otimes x_0$, and $\tilde{v} = v - \mathbf{1} \otimes v_0$. Noting that

$$-(L + B) x(t-r) + B1 \otimes x_0(t-r) = -(L + B) \tilde{x}(t-r), \quad (5)$$

system (4) can be rewritten as

$$\dot{\varepsilon} = C\varepsilon(t) + E\varepsilon(t-r), \quad (6)$$

where

$$\begin{aligned} \varepsilon &= \begin{pmatrix} \tilde{x} \\ \tilde{v} \end{pmatrix}, & C &= \begin{bmatrix} 0 & I_n \\ 0 & -kI_n \end{bmatrix}, \\ E &= \begin{bmatrix} 0 & 0 \\ -H & 0 \end{bmatrix}, & H &= L + B. \end{aligned} \quad (7)$$

Before the discussion of the consensus problem, we introduce Lemma 3 for time-delay system (6). Consider the following system:

$$\begin{aligned} \dot{x} &= f(x_t), \quad t > 0, \\ x(\theta) &= \varphi(\theta), \quad \theta \in [-\tau, 0]. \end{aligned} \quad (8)$$

Lemma 3 (Lyapunov-Razumikhin theorem). *Let Φ_1, Φ_2, and Φ_3 be continuous, nonnegative, and nondecreasing functions with $\Phi_1(s) > 0$, $\Phi_2(s) > 0$, and $\Phi_3(s) > 0$ for $s > 0$, and $\Phi_1(0) = 0$ and $\Phi_2(0) = 0$. For system (8), suppose that the function $f : C([-\tau, 0], R^n) \rightarrow R$ takes bounded sets of $C([-\tau, 0], R^n)$ in bounded sets of R^n. If there is a continuous function $V(t, x)$ such that*

$$\Phi_1(\|x\|) \le V(t, x) \le \Phi_2(\|x\|), \quad t \in R, \ x \in R^n. \quad (9)$$

In addition, there exists a continuous nondecreasing function $\Phi(s) > s$, $s > 0$, such that

$$\begin{aligned} &\dot{V}(t, x) \le -\Phi_3(\|x\|), \\ &\text{If } V(t+\theta, x(t+\theta)) < \Phi(V(t, x(t))), \ \theta \in [-\tau, 0], \end{aligned} \quad (10)$$

then the solution $x = 0$ is uniformly asymptotically stable.

Lemma 4. *The matrix $\mathbf{H} = \mathbf{L} + \mathbf{B}$ is positively stable if and only if node 0 is globally reachable in G.*

The proof of Lemma 4 can be looked up in [32].

Theorem 5. *For system* (6), *take*

$$k > \frac{\overline{\mu}}{2\overline{\lambda}} + 1, \tag{11}$$

where $\overline{\mu} = \max\{$*eigenvalue of* $\overline{P}HH^T\overline{P}\}$, $\overline{\lambda}$ *is the smallest eigenvalue of* $\overline{P}$, *and* $\overline{P}$ *is a positive definite matrix. Then, when delay upper bound* τ *is sufficiently small,*

$$\lim_{t\to\infty} \varepsilon(t) = 0, \tag{12}$$

if node 0 is globally reachable in $\overline{G}$.

Proof. Since node 0 is globally reachable in $\overline{G}$, from Lyapunov theorem, there exists a positive definite matrix $\overline{P}$ satisfying

$$\overline{P}H + H^T\overline{P} = I_n. \tag{13}$$

Take a Lyapunov-Razumikhin function $V(\varepsilon) = \varepsilon^T P\varepsilon$, where

$$P = \begin{bmatrix} k\overline{P} & \overline{P} \\ \overline{P} & \overline{P} \end{bmatrix} \tag{14}$$

is positive definite.

By Leibniz-Newton formula,

$$\begin{aligned} \varepsilon(t-r) &= \varepsilon(t) - \int_{-r}^{0} \dot{\varepsilon}(t+s)\,ds \\ &= \varepsilon(t) - C\int_{-r}^{0} \varepsilon(t+s)\,ds - E\int_{-2r}^{-r} \varepsilon(t+s)\,ds. \end{aligned} \tag{15}$$

From $E^2 = 0$, the delayed differential equation (6) can be rewritten as

$$\dot{\varepsilon} = F\varepsilon - EC\int_{-r}^{0} \dot{\varepsilon}(t+s)\,ds, \tag{16}$$

where $F = C + E$. As $2a^Tb \le a^T\psi a + b^T\psi^{-1}b$ holds for any appropriate positive definite matrix ψ, we have

$$\begin{aligned} \dot{V}(\varepsilon) &= \varepsilon^T\left(F^TP + PF\right)\varepsilon - 2\varepsilon^T PEC\int_{-r}^{0} \varepsilon(t+s)\,ds \\ &\le \varepsilon^T\left(F^TP + PF\right)\varepsilon + r\varepsilon^T PECP^{-1}C^TE^TP\varepsilon \\ &\quad + \int_{-r}^{0} \varepsilon^T(t+s)\,P\varepsilon(t+s)\,ds. \end{aligned} \tag{17}$$

Take $\Phi(s) = qs$ for $q > 1$. In the case of

$$V(\varepsilon(t+\theta)) < qV(\varepsilon(t)), \quad -\tau \le \theta \le 0, \tag{18}$$

we have

$$\dot{V}(\varepsilon) \le \varepsilon^T\left(F^TP + PF\right)\varepsilon + r\varepsilon^T\left(PECP^{-1}C^TE^TP + qP\right)\varepsilon. \tag{19}$$

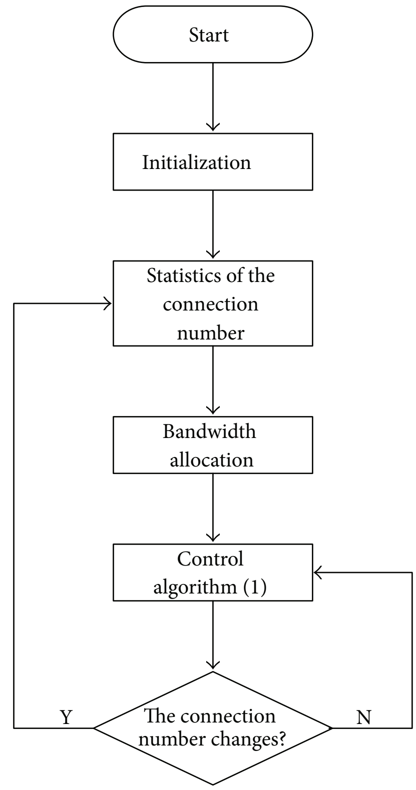


Figure 1: Program flow chart.

If k satisfies (11), $F^TP + PF > 0$ according to Lemma 4 and Schur complements theorem. Let $\lambda_{\min}$ denote the minimum eigenvalue of $F^TP + PF$. If we take

$$r < \frac{\lambda_{\min}}{\left\|PECP^{-1}C^TE^TP\right\| + q\left\|P\right\|}, \tag{20}$$

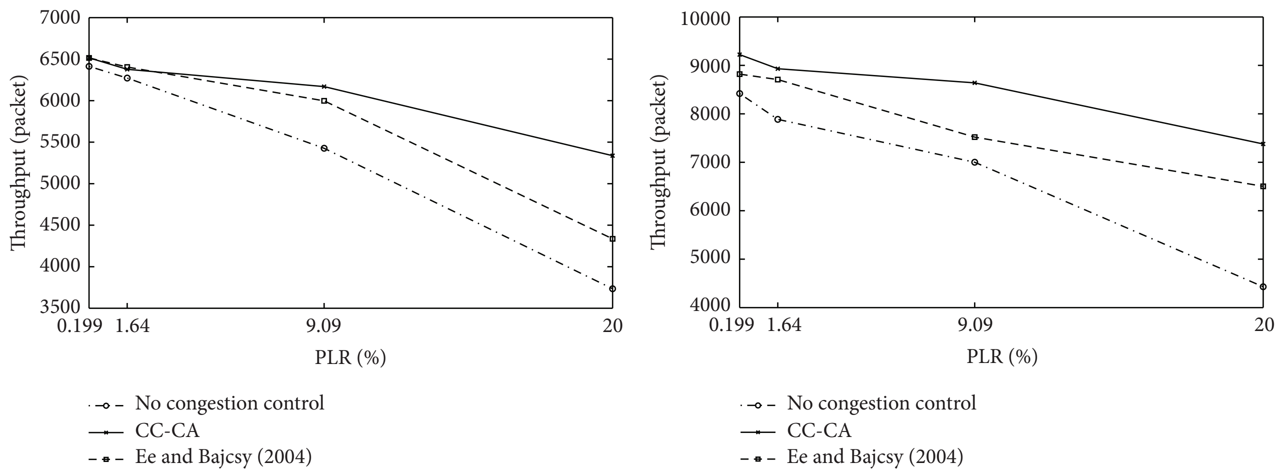
then $\dot{V}(\varepsilon) \le -\eta\varepsilon^T\varepsilon$ for some $\eta > 0$. Therefore, the conclusion follows from Lemma 3. □

Remark 6. There are two limiting conditions in Theorem 5. Firstly, the delay upper bound τ is sufficiently small. The timeout time in the retransmission timeout is small enough with initial value 3 s. Secondly, node 0 is globally reachable in $\overline{G}$. The leader (node 0) is the sink of WSN, through which all the information collected by the sensors is transmitted. So the sink is globally reachable in WSN topology.

Theorem 5 proves that the CC-CA guarantees the convergence of the system error; in other words, the data sent rates for all nodes converge equally to the sink's. The proposed algorithm maintains an equilibrium state for the whole WSN, avoiding congestion. Figure 1 shows the program flow chart of the CC-CA.

5. Simulation

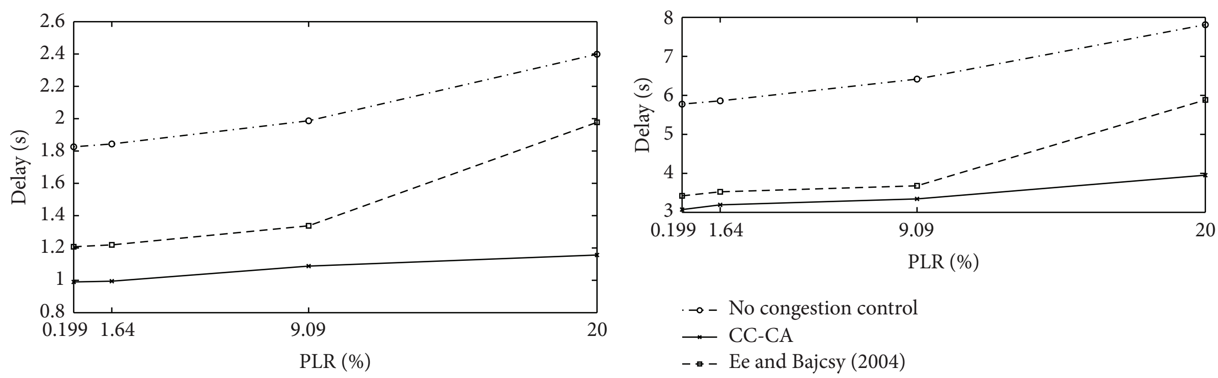
This section studies the performance of the proposed CC-CA under a general wireless sensor network configuration.



(a) 2 sources

(b) 8 sources

Figure 2: Throughput in different PLRs.



(a) 2 sources

(b) 8 sources

Figure 3: Average delay in different PLRs.

The simulation environment models a sensor network with 200 nodes deployed randomly over an area of 300 × 300 m. The coordinate of the sink is (144, 168). Simulations are conduced using ns-2 network simulator, and the simulation time is 300 sec.

Test 1. In order to verify the validity of the proposed algorithm in variable condition, the number of the data source is set to 2, 5, 8, and 10, respectively. The throughput and the drop ratio are shown in Table 1 for the different connection numbers. The suitable rate for the sink is assigned to all the other sensors, reducing the packet cumulate in the sensor buffer. As discussed in Section 1, the energy usage is the key factor in WSN. The lost parameter η is used to measure the energy efficiency of the whole network, which is defined in [33]. The lost parameter η at distinct rate is shown in Table 2.

Test 2. Test 2 studies the performance of CC-CA by the channel error. The Gilbert model [34] is used to structure the packet loss ratio (PLR) in wireless link. The PLRs involved in Test 2 are provided in Table 3, where p means the probability from "good" state (0% PLR) to "bad" state (100% PLR); q is the probability from "bad" state to "good" one. The throughput and the average delay with different PLRs are shown in Figures 2 and 3, respectively. The performance of CC-CA is tested in varying degrees of congestion by changing the number of the data sources. In our test, most of the packet drop is caused by the link error; by contrast to the traditional wired network, most of the packet losses (sometimes represented as duplicate acknowledgements) are suggested as network congestion notifications, and the end host reduces the transmit rate.

Simulation results indicate that our CC-CA is able to utilize the network resources more efficiently with low drop ratio and low delay time.

6. Conclusion

The congestion problem is unavoidable because of the many-to-one characteristic in the wireless sensor network, which causes the channel quality deterioration and the loss ratio

Table 1: Throughput and drop ratio within different connection numbers.

	Throughput (packet)				Packet drop ratio (%)			
No.	2	5	8	10	2	5	8	10
No congestion control	7047	6457	8860	12926	0.09	0.3	0.38	0.45
Reference [13]	7052	6621	9023	13454	0.08	0.25	0.33	0.39
CC-CA	6932	6655	9707	16598	0.08	0.26	0.27	0.32

Table 2: Loss parameter η at distinct rate.

Time interval(s)	0.02	0.05	0.08	0.1
No Congestion control	1.857	0.923	0.667	0.235
CC-CA	1.101	0.614	0.558	0.222

Table 3: Different PLRs in simulation.

P	q	Packet loss rate (PLR)
0.001	0.5	0.199%
0.01	0.6	1.64%
0.05	0.5	9.09%
0.1	0.4	20%

rise. It leads to packets drops at the buffers, increased delays, wasted energy and requires retransmissions. Based on the consensus problem of the complex network, a novel congestion control algorithm (CC-CA) is introduced in this paper, which provides a better performance. At the same time, only the single-sink topology is discussed in the paper, so the multisink sensor network is the further research. On the other hand, all nodes are considered to be sharing the link capacity fairly in the simulation, so an efficient bandwidth allocation protocol is needed which will improve our algorithm.

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