Research Article
A Reliable Transport Protocol with Prediction Mechanism for Urgent Information in Wireless Sensor Networks

Zhenchun Wei, Lin Feng, Jianghong Han, Xiangwei Xu, and Hao Peng

1 School of Computer and Information, Hefei University of Technology, Hefei 230009, China
2 Research Institute of Hefei University of Technology in Changzhou, Changzhou 213164, China

Correspondence should be addressed to Lin Feng; fenglin@hfut.edu.cn

Received 26 July 2013; Accepted 8 November 2013

1. Introduction

A wireless sensor network (WSN) consists of numerous sensor nodes. These sensor nodes are self-organized by wireless communication and transfer surrounding environmental data to observers. Due to characteristics including low cost, robustness, and survivability, sensor nodes can be deployed densely in large-scale areas [1, 2]. Although a WSN is designed to collect data when an emergency occurs within the monitoring region, sensor nodes may still suffer from some problems incited by the rapid increase of data throughput. The problems include congestion, increase of network transmission delay, and decrease of network throughput, which are not conducive to transfer data timely and reliably [3]. Thus, congestion control mechanism is also in great need to ensure timely and reliable data transmission in WSNs.

Currently, there are mainly two issues dealing with congestion detection and rate adjustment in congestion control mechanisms [4, 5]. Channel load [6, 7], length of buffer queue [8], the ratio of node service rate and arrival rate [9], and so forth, are adopted as criterion of congestion detection in most research studies. Such detection mechanisms not only fail to reflect the possibility of overflow of the node queue length timely and accurately but also ignore that the occurrence of congestion is a continuous gradual process. In addition, in rate adjustment phase, mostly the original rate [10, 11] is adjusted to defer or reduce the amount of data flow into the network, so as to achieve the purpose of reducing congestion in traditional congestion control mechanisms. As these congestion control mechanisms cannot model the process of event that occurs realistically, they cannot guarantee timely and reliable transmission of emergency information.

PCCP [6] is a typical protocol based on priority control. In this protocol, each node is assigned with a priority, and arrival time of interactive packet in a queue is calculated to detect congestion. Rate adjustment is conducted according to the priority of each node. The deficiency of PCCP is that diverse needs of reliable data are not taken into account although the priority mechanism is adopted [12].

In RTP-UI [13], the priority queue mechanism and the state machine model are introduced into the protocol. In congestion detection mechanism, the congestion level of each node is evaluated by combining the length of buffer queue
with change rate of the queue length. Working states of nodes are divided into six states. Different rate adjustment mechanisms are adopted depending on different states. Compared with traditional congestion control mechanisms, the advantage of RTP-UI is that it reflects the real situation of emergencies by taking the gradual process of node congestion and the diversity of data transmission into account. The disadvantage of RTP-UI is that the analysis on gradual process of congestion of the node itself is not comprehensive, which cannot indicate the current congestion state of the network timely and accurately.

In this paper, emergency that occurred within wireless monitoring region is studied intensively. According to three characteristics including suddenness [14], timeliness [15], and the diversity for reliability in emergency data, a reliable transport protocol (PMUI) with prediction mechanism for WSN to deliver urgent information is designed and analyzed. The congestion control mechanism of RTP-UI is improved in PMUI. It not only combines the prediction mechanism with the priority control mechanism but also obtains eight different node working states through the comprehensive analysis of joint change rate of queue, joint queue length, expected queue length, and expected joint change rate of queue. It also adopts different rate adjustments depending on their different states. Compared with RTP-UI, PMUI is able to accurately determine the current network congestion and timely adjusts node transmission rate by the way of analyzing probability of congestion in future by prediction mechanism.

2. Improvement of RTP-UI Congestion Control Mechanism

2.1. Queue Model. Each node has three priority queues, that is, high, medium and low priority queue, denoted as HP, MP, and LP. These three priority queues are assigned with different weights, denoted as \( \omega_h, \omega_m, \omega_l \), according to their importance. Some provisions are defined as follows. Header part of each queue includes not only the change rate of node queue \( \rho_i \), the queue length \( QL_i \), but also the expected queue length \( QL_{exp_i} \) and the expected joint change rate of queue \( \rho_{exp_i} \), where \( i \in \{h, m, l\} \) and \( QL_{max} \) is the maximum length of a queue.

2.2. Congestion Evaluation Mechanism. In PMUI, queue length changes are considered on the current and previous cycles, and the expected queue length \( QL_{exp_i} \) and expected joint change rate of queue \( \rho_{exp_i} \) are introduced. Required queue length for the next cycle is preestimated by analyzing variables \( QL_{exp_i} \) and \( \rho_{exp_i} \) in the protocol, and the current queue space is compared with predicted required space of the next time slot, so as to judge whether the danger of queue overflow exists or not.

**Definition 1.** Joint change rate of queue is defined as follows:

\[
\rho = \frac{\sum \omega_i \cdot \rho_i}{\sum \omega_i}, \quad i \in \{h, m, l\},
\]

where \( \rho_i = (QL_{i, curr} - QL_{i, last})/(QL_{max} - QL_{i, curr}) \), \( QL_{i, curr} \neq QL_{max} \), \( i \in \{h, m, l\} \). The current and previous queue length in a cycle for node \( i \) are denoted as \( QL_{i, curr} \) and \( QL_{i, last} \), respectively.

**Definition 2.** Joint queue length is defined as follows:

\[
QL_u = \sum \omega_i \cdot QL_i, \quad i \in \{h, m, l\}.
\]

**Definition 3.** Expected queue length is defined as follows:

\[
QL_{exp_i} = \delta \left( QL_{i, curr} - QL_{i, last} \right) + (1 - \delta) \left( QL_{i, last} - QL_{i, thr} \right),
\]

where \( QL_{i, thr} \) is queue length of the second reciprocal cycle for node \( i \).

**Definition 4.** Expected change rate of a queue is defined as follows:

\[
\rho_{exp} = \frac{\sum \omega_i \cdot \rho_{exp_i}}{\sum \omega_i}, \quad i \in \{h, m, l\},
\]

where \( \rho_{exp_i} = QL_{exp_i} / (QL_{max} - QL_{i, exp}) \), \( QL_{i, exp} \neq QL_{max} \), \( i \in \{h, m, l\} \).

Working conditions are divided into eight by comprehensive analysis of joint queue length \( QL_u \), \( \rho \), \( QL_{max} - QL_{i, exp} \), and \( QL_{exp} \) of nodes in PMUI. Different working conditions correspond to different working states.

**State 1.** When a node satisfies Condition 1, the joint queue length \( QL_u \) is 0, and it indicates that the node queue is empty, and the node will enter State 1.

**Condition 1.**

\[
QL_u = 0, \quad \rho = 0.
\]

**State 2.** When a node satisfies Condition 2, the node will enter State 2. At this time, \( QL_{exp} \) is less than or equal to the remaining queue length of current node, and the joint change rate of the queue is less than \( \Delta_{thr} \), indicating that the node is in normal working condition.

**Condition 2.**

\[
0 < QL_u \leq (1 - \alpha) QL_{max},
\]

\[
QL_{exp} \leq (QL_{max} - QL_{i, exp}),
\]

\[
0 < \rho < \Delta_{thr}.
\]

**State 3.** When a node satisfies Condition 3, the joint change rate of the queue is less than or equal to 0, indicating that the queue length of the node is gradually decreasing. At this time, the node will enter State 3, and it is in normal working condition.
Condition 3.
\[ 0 < QL_u \leq (1 - \alpha) QL_{max}, \]
\[ QL_{exp_i} \leq (QL_{max} - QL_{curr_i}), \quad (7) \]
\[ \rho \leq 0. \]

State 4. When a node satisfies Condition 4, \( QL_u \) is less than \( (1 - \alpha) QL_{max} \) and the joint change rate of the queue is greater than \( \Delta_{thr} \), indicating that an emergency occurs in the network, and the queue length of the node is rapidly increasing. At this time, the node will enter State 4. Primary rate adjustment mechanism will start.

Condition 4.
\[ 0 < QL_u \leq (1 - \alpha) QL_{max}, \]
\[ \rho > \Delta_{thr}. \quad (8) \]

State 5. When there are one or more queues in the node priority queue, of which the remaining length is between \( QL_{exp}/2 \) and \( QL_{exp} \), it indicates the increasing potentiality of overflow of this node in the next cycle. At this time, we do not consider the impact of \( QL_u \) and \( \rho \), and the node immediately enters State 5, and the primary rate adjustment mechanism will start.

Condition 5.
\[ QL_{exp} > (QL_{max} - QL_{curr_i}) \geq \frac{QL_{exp}}{2}. \quad (9) \]

State 6. When a node satisfies Condition 6, \( QL_u \) is between \( (1 - \alpha) QL_{max} \) and \( \alpha QL_{max} \), \( QL_{exp} \) is less than or equal to queue remaining length of current node. At this time, the node will enter State 6, and the primary rate adjustment mechanism will start.

Condition 6.
\[ (1 - \alpha) QL_{max} < QL_u < \alpha QL_{max}, \]
\[ QL_{exp} \leq (QL_{max} - QL_{curr_i}). \quad (10) \]

State 7. When \( QL_u \) is greater than or equal to \( \alpha QL_{max} \), it means that the node is falling into severe congestion, and the probability of packet loss due to queue overflow is increasing. At this time, the node will enter State 7, and the senior rate adjustment mechanism will start.

Condition 7.
\[ QL_u \geq \alpha QL_{max}. \quad (11) \]

State 8. When a node satisfies Condition 8, it indicates that the probability of queue overflow is increasing in a node. At this time, \( QL_u \) and \( \rho \) cannot fully reflect the node queue congestion. Thus, the node will enter State 8, and the senior rate adjustment mechanism will start.

Condition 8.
\[ QL_{max} - QL_{curr_i} \leq \frac{QL_{exp}}{2}, \quad (12) \]

where \( \alpha \) is a customized constant with value between 0.5 and 1 and \( \Delta_{thr} \) is a fixed threshold value between 0 and 1. In order to adjust the working state of the node, the node will conduct a congestion evaluation every second.

The improved node state transition diagram is shown in Figure 1. As shown in the figure, we can figure out the transformational relation of each state, where S1 to S8 in the figure represent State 1 to State 8.

2.3. Rate Adjustment Mechanism. Node states of rate adjustment are divided into normal rate adjustment, primary rate adjustment, and senior rate adjustment in PMUI. The normal rate adjustment mechanism adopts the rate adjustment mechanism utilized in reference [13]. In order to perform a comprehensive analysis in the primary rate adjustment and senior rate adjustment mechanism in PMUI, the joint change rate of queue is combined with the expected change rate of queue. It is more flexible to adjust the transmission rate of a node and more reliable to transfer data.

2.3.1. Normal Rate Adjustment Mechanism. When a node is in State 2 or State 3, the node is in normal working condition. At this time, normal rate adjustment mechanism is used. According to the rate adjustment mechanism in reference [13], we can obtain the average service rate of the sink node, as shown in the following formula:

\[ v'_\text{sink} = \frac{1}{(1 - \theta) T'_{\text{sink}} + \theta T''_{\text{sink}}}, \quad (13) \]

where \( \theta \) is a constant between 0 and 1 and \( T'_{\text{sink}} \) and \( T''_{\text{sink}} \) are the average service time of sink node in the current and previous cycle, respectively.

Starting from the sink node, each node \( i \) in the network is evaluated in turn by formula (14) and broadcasts initial
maximum service rate of its child node \( j \), where \( p^G_j \) is the global priority of node \( j \), generated by cumulative weights of current producing data type in the node. \( C_i \) is the collection of child nodes of node \( i \), and \( \sum_{j \in C_i} p^G_j \) is the sum of global priority in all child nodes of node \( i \):

\[
v^\text{max}_j = v_j \frac{p^G_j}{\sum_{j \in C_i} p^G_j}, \quad j \in C_i. \tag{14}
\]

After each dispatching cycle of node, the rate of each child node \( j \) is readjusted by formula (15), where \( v_j \) and \( \sum_{j \in C_i} v^{}_j \) are the output and input rate of node \( i \), respectively, and \( \alpha \) is a constant:

\[
v_j = v^{}_j + \frac{p^G_j}{\sum_{j \in C_i} p^G_j} \left( \alpha v^{}_j - \sum_{j \in C_i} v^{}_j \right), \quad i \in C_i. \tag{15}
\]

2.3.2. Primary Rate Adjustment Mechanism. As we can see from the improved node state transition diagram, we draw that when a node is in State 4, 5, or 6, the possibility of overflow is increasing in the congestion queue because of the increase of node’s data flow. It will result in the increasing probability of node’s packet loss. Therefore, the node needs to improve its service rate to cancel out the increase of queue length by the primary rate adjustment mechanism.

Primary rate of node \( j \) is calculated by formula (16), where \( v^{}_j \) is rate of its parent node and \( \lambda \) and \( \beta \) are the rate controlling factors. Assume that the rate of any node cannot exceed the rate of its parent node. According to formula (17), uncongested sibling node \( k \) and node \( j \) will adjust the rate. The parent node’s remainder bandwidth is allocated according to their own priority:

\[
v^{}_j = \min \left\{ v^{}_j + \beta \cdot p^\text{exp} + \lambda \cdot \rho, v^{}_j \right\}, \tag{16}
\]

\[
v^{}_k = \left( v^{}_i - v_j \right) \frac{p^G_k}{\sum_{k \in C_j \cup k \neq k} p^G_k}. \tag{17}
\]

2.3.3. Senior Rate Adjustment Mechanism. When a node is shifted to State 7 or 8, the node queue length is greater than \( Q_{\text{max}} \) or \( Q_{\text{max}} - Q_{\text{curr}} \) is less than the half of \( Q_{\text{curr}} \), causing a higher packet loss probability because of the queue overflow. As the primary rate adjustment mechanism cannot guarantee reliable urgent data transmission, the senior rate adjustment mechanism is used, as shown in formula (18), where \( \lambda \) and \( \beta \) are defined in the formula (16):

\[
v^{}_i = v^{}_i + v^{}_j \min \left\{ \beta \cdot p^\text{exp} + \lambda \cdot \rho, 1 \right\}. \tag{18}
\]

It means that low level rate adjustment mechanism cannot work well even the node gets all of its parent node’s bandwidth, and high level rate adjustment mechanism is adopted. Then in order to reduce congestion, bandwidth of its parent node and its sibling node is reallocated.

### 3. Design and Analysis of Simulation Experiments

In order to verify performance of PMUI, we use two performance indicators, including delay and packet loss rate, as the evaluation criterion. We also compare the performances of PMUI with RTP-UI and PCCP protocols. We use the same topology model used in RTP-UI for simulation and only consider the node queue overflow congestion. The topology model for simulation is shown in Figure 2. It is assumed that the node \( c \) is off during 10–40 s, indicating that the rate of node \( c \) becomes 0 and assumed that node \( c \) detects emergencies during 60–90 s, which will result in huge bunch of persistent data suddenly.

Simulation parameter settings are shown in Table 1.

As shown in Figure 3(a), the packet loss rates of HP approach zero in PMUI and RTP-UI. From Figures 3(b) and 3(c), we can see that the packet loss rates of MP and LP are much smaller than those in PCCP. Compared with RTP-UI, the average packet loss rate of PMUI is lower. PMUI has higher reliability for emergency information transmission.

Comparison results of delay of these three kinds of data flows are shown in Figure 4. The average delay of HP, MP, and LP in PMUI is less than that in RTP-UI and PCCP, and the delay of HP is less than the delay of MP and LP. The average delay of LP has the largest gap. In the event of an emergency, PMUI is more effective to reduce transmission delay of emergency information.

From Figures 3 and 4, both packet loss rate and delay fluctuate at 10 s because of the closedown of node \( c \). But they
all recover soon. Although emergencies occur during 60–90 s, RTP-UI and PMUI both work well since the continuous variation of congestion is considered in both of them. RTP-UI and PMUI both perform better in higher priority queues due to their priority control mechanism. With prediction mechanism, PMUI performs better than RTP-UI when emergencies occur.

4. Conclusions

In this paper, a reliable transport protocol with prediction mechanism for urgent information (PMUI) is proposed. Considering the characteristics of emergency information comprehensively, prediction mechanism and priority control mechanism are utilized in PMUI. We design a congestion detection method based on queue priority, change rate of queue length, expected queue length, and expected change rate of queue length. According to the degree of current congestion and the queue tendency in next cycle with prediction mechanism, node working states are divided into eight different ones, so as to adopt a different rate control mechanism. Compared with RTP-UI, PMUI is better in ensuring reliable transmission of emergency information in WSNs.

Acknowledgments

The author would like to acknowledge the financial support of the Special Fund Project of the National Natural Science Foundation of China (no. 61370088), National IOT Development (no. MOIIT (2012)583), Doctoral Fund of
Ministry of Education of China (no. 20100111110004 and no. 20120111100001), Natural Science Foundation of Jiangsu Province (no. BK2011236), Natural Science Foundation of Anhui Province (no. 1208085QF113), and S&T Cooperation Program of Anhui Province of China (no. 1303063009).

References

[1] T. Yang, Y. Sun, J. Taheri, and A. Y. Zomaya, “DLS: a dynamic local stitching mechanism to rectify transmitting path fragments in wireless sensor networks,” Journal of Network and Computer Applications, vol. 36, no. 1, pp. 306–315, 2013.

[2] L. Hui-yu, W. Jian-xin, and Z. Zhi, “Survey of congestion control technology for wireless sensor networks,” Computer Science, vol. 36, no. 5, pp. 7–11, 2009.

[3] T. Yang, C. Kang, and G. Nan, “An energy-efficient and fault-tolerant convergecast protocol in wireless sensor network,” International Journal of Distributed Sensor Networks, vol. 2012, Article ID 429719, 8 pages, 2012.

[4] L. Liang, D. Gao, Y. Qin, and H. Zhang, “An adaptive congestion-aware MAC protocol for wireless sensor networks,” in Proceedings of the 3rd IEEE International Conference on Broadband Network and Multimedia Technology (IC-BNMT ’10), pp. 1074–1078, Beijing, China, October 2010.

[5] J.-J Jiang, G.-W Bai, and A. Yan, “Rate adjustment algorithm based on congestion levels for WSNs,” Microelectronics & Computer, vol. 28, no. 5, pp. 118–121, 2011.

[6] C. G. Wang, K. Sohraby, V. Lawrence, L. Bo, and H. Yueming, “Priority-based congestion control in wireless sensor networks,” in Proceedings of the IEEE International Conference on Sensor
[7] T. Yong and G. Zheng-hu, "An adaptive role-based congestion control for DTN," *Computer Engineering & Science*, vol. 35, no. 1, pp. 52–56, 2013.

[8] G.-D. Sun, M.-H. Liao, and S. Qiu, "A congestion control scheme in wireless sensor networks," *Journal of Electronics and Information Technology*, vol. 30, no. 10, pp. 2494–2498, 2008.

[9] B. Hull, K. Jamieson, and H. Balakrishnan, "Mitigating congestion in wireless sensor networks," in *Proceedings of the Second International Conference on Embedded Networked Sensor Systems (SenSys ’04)*, pp. 134–147, Baltimore, Md, USA, November 2004.

[10] A. Sridharan and B. Krishnamachari, "Explicit and precise rate control for wireless sensor networks," in *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems (SenSys ’09)*, pp. 29–42, Berkeley, Calif, USA, November 2009.

[11] M. M. Bhuiyan, I. Gondal, and J. Kamruzzaman, “CAM: Congestion avoidance and mitigation in wireless sensor networks,” in *Proceedings of the IEEE 71st Vehicular Technology Conference (VTC ’10)*, Taipei, Taiwan, May 2010.

[12] L. Q. Tao and F. Q. Yu, "ECODA: enhanced congestion detection and avoidance for multiple class of traffic in sensor networks," *IEEE Transactions on Consumer Electronics*, vol. 56, no. 3, pp. 1387–1394, 2010.

[13] L.-L. Liang, D.-Y. Gao, Y.-J. Qin, and H.-K. Zhang, "A reliable transport protocol for urgent information in wireless sensor networks," *Journal of Electronics and Information Technology*, vol. 34, no. 1, pp. 95–100, 2012.

[14] H. Higaki, "NeBuST: low-latency congested sensor data transmission protocol," in *Proceedings of the International Conference on Communications and Information Technology (ICCIT ’11)*, pp. 36–42, Aqaba, Jordan, March 2011.

[15] M. M. Bhuiyan, I. Gondal, and J. Kamruzzaman, “CODAR: congestion and delay aware routing to detect time critical events in WSNs,” in *Proceedings of the International Conference on Information Networking (ICOIN ’11)*, pp. 257–362, Kuala Lumpur, Malay, January 2011.
