Transmission scheduling for tandemly-connected sensor networks with heterogeneous packet generation rates

Ryosuke Yoshida, Masahiro Shibata and Masato Tsuru

Abstract A tandemly-connected multi-hop wireless sensor network model is studied. Each node periodically generates packets in every cycle and relays the packets in a store-and-forward manner on a lossy wireless link between two adjacent nodes. To cope with a considerable number of packet losses, we previously proposed a packet transmission scheduling framework, in which each node transmits its possessing packets multiple times according to a static time-slot allocation to recover or avoid packet losses caused either by physical conditions on links or by interference of simultaneous transmissions among near-by nodes. However, we assumed that the packet generation rate is identical over all nodes, which is not always realistic. Therefore, in this paper, we enhance our work to the case of heterogeneous packet generation rates. We derive a static time-slot allocation maximizing the probability of delivering all packets within one cycle period. By using an advanced wireless network simulator, we show its effectiveness and issues to be solved.

1 Introduction

We focus on a multi-hop wireless network model in which network nodes are tandemly arranged and serially connected by unreliable lossy links. Each node generates a certain number of packets in every one cycle period and also relays them

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in a store-and-forward manner on a low-cost wireless link between two adjacent nodes. Generated packets are finally forwarded to one of gateways located at both ends of the network and sent to a central server via Internet. This type of configuration is often seen in sensor networks to monitor facilities (e.g., a power transmission tower's network) in a geographically elongated field without a wide-area infrastructural network.

A problem in such networks is frequent happening of packet losses caused either by attenuation and fading in environmental conditions (e.g., restricted placement of nodes) or by interference of simultaneous data transmissions among near-by nodes especially with omnidirectional antenna. This problem is common in multi-hop wireless networks, and a wide range of studies have been devoted over decades In this paper, to mitigate interference of simultaneous transmissions, we adopt a Time Division Media Access (TDMA)-based scheduling because it is efficient and suitable in centrally-managed stationary network configurations. On TMDA scheduling, there are a number of studies. A conflict-free TDMA scheduling for multi-hop wireless networks to minimize an end-to-end delay was discussed [1]. Two centralized algorithms for the shortest schedules for sensor networks with a few central data collectors were proposed [2]. Wireless mesh networks with multiple gateway nodes were studied [3] to maximize the traffic volume transferred between the mesh network and the central server via gateways. An online and distributed scheduling for lossy networks was studied [4] to provide hard end-to-end delay guarantees. Most of them focused on avoiding interference of simultaneous data transmissions on general network topologies by using the conflict graph or some heuristics. However, they do not explicitly consider retransmissions. On the other hand, our previous work [5, 6] proposed a packet transmission scheduling framework to derive an optimal number of retransmissions for each packet on each link while being restricted to tandemly-connected topologies with two gateways at the edges; which has not been well studied. We analytically derived a static time-slot allocation that maximizes the probability of delivering all packets in one cycle period but only in the case that each node generates one packet every cycle. Therefore, in this paper, we deal with a transmission scheduling with heterogeneous packet generation rates.

2 Proposed method

2.1 System model

In this study, we assume a tandemly-connected multi-hop wireless network model in which nodes are tandemly arranged and serially connected by unreliable lossy links. Each node is a sensor node that periodically generates packets and also relays those packets in a store-and-forward manner between two adjacent nodes. Packets generated by each sensor node are finally forwarded to one of gateways located at both ends of the network and are sent to a central server via Internet.

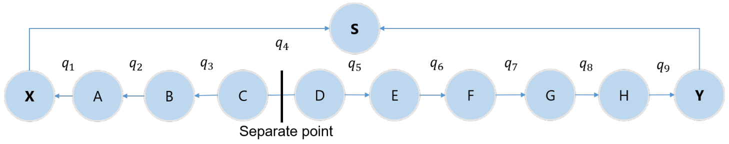


Fig. 1: Tandemly-connected multi-hop wireless network model (3-5 model).

The model consists of n nodes and two gateways X,Y at both ends as illustrated in Fig. 1. The sensor nodes and wireless links are separately numbered from left to right. Each link is lossy and half-duplex. A transmission of packet by a node affects both links connected to that node. Therefore, to avoid transmission interference, two nodes within two-hop distance should not transmit packets in the same direction simultaneously (i.e., on the same time-slot). The data-link layer does not provide any advanced packet loss recovery scheme such as Automatic Repeat-reQuest (ARQ) and any advanced transmission power adaptation, in which a proactive redundant packet transmission by each node is required to cope with packet losses. Therefore, each packet from an upstream node is stored and redundantly transmitted to a downstream node in scheduled slots.

The packet loss rate of link j is defined as q_j $(0 < q_j < 1)$, and the packet generation rate of node i is defined as integer r_i. Node i generates r_i packets at (or before) the beginning of a cycle period D and those packets are forwarded to the gateway either X or Y, which are sent to the central server S. The central server S knows the values q_j and r_i for any j and i, and designs a global static time-slot allocation to schedule the packet transmission at each node based on these values. Thus, it can consider not only the loss rates of links but also the packet generation rates of nodes while avoiding interference among near-by nodes based on a static interference avoidance policy considering the hop distance between nodes. The goal of the scheduling is to deliver all generated packets to either one of gateways along the lossy links during a cycle period D with a high success probability and fairness among packets from different nodes.

To design a time-slot allocation, we need to decide a routing direction of packets (i.e., to which direction the packets are transmitted on each link). We call it a path model. In this paper, we adopt the model “the dual separated (DS) path model” to determine the gateway for each node to forward packets to. In the DS path model, two independent paths are separated at a separation (unused) link. Any node at the left of the separation link will forward packets to the left gateway X and any node at the right of the separation link will forward to the right gateway Y. It is called l-r model where l and r are the number of nodes located at the left and the right of the separation link, respectively. In Fig. 1, there are 7 candidates as the separation link for the DS path model. For example, if the link between nodes 3 and 4 is the separation link, the path model is 3-5 model (3-5 model and 4-4 model are focused on in this paper.).

On a path model, based on the method explained in the next subsection, an optimal static time-slot allocation is derived by computing the theoretical probability that all packets are successfully delivered to either one of gateways. To find the optimal static time-slot allocation including a path model selection, we examine all reasonable path models one by one in such a manner. Finally we choose a best combination of a path model and a slot allocation in terms of maximizing the above success delivery probability.

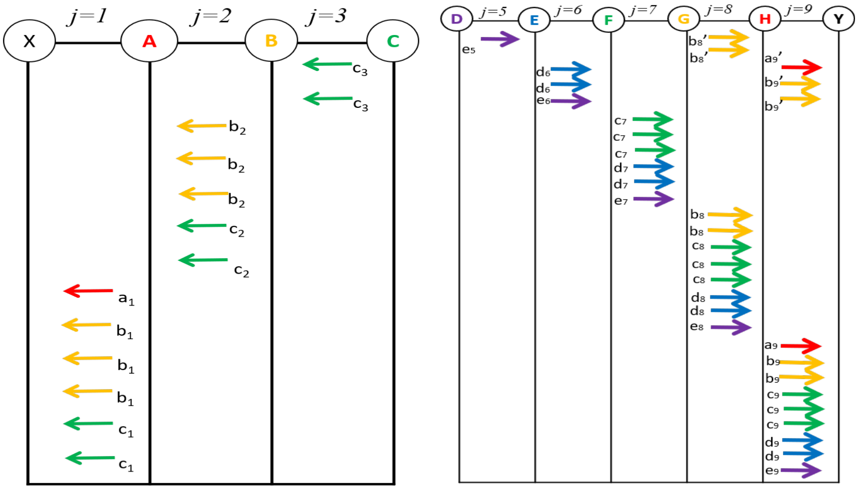
2.2 Static slot allocation for redundant transmission scheduling

On a given path model, our method can derive a global time-slot allocation for redundant transmission scheduling. Let T be the total number of slots in one cycle period D, i.e., D/T is the time duration of one time-slot. A global time-slot allocation allocates s_{ij} slots for node i to send its packets via link j in T total time-slots. According to the allocation, each node redundantly transmits possessed packets (that is originally generated by node i) on downstream link j in s_{ij} times in the following order. The packet generated by itself is sent first in the allocated times, then the packets generated by other nodes located at closer upstream are forwarded earlier in the allocated times. If a packet is lost in upstream and does not reach the node, the slots allocated to the packet is used for the next packet. The derived time-slot allocation is optimal in the sense that it theoretically maximizes the success probability of delivering all packets within one cycle period, to cope with packet losses on links by redundantly transmitting each packet allocated times. To be more exact, let M_k be the success probability of delivery for packets from node k, i.e., the probability that all r_k packets generated by node k are successfully delivered to either one of two gateways in T time-slots. Then the derived time-slot allocation aims to maximize the product $\prod_{k=1}^{n} M_k$. This is the maximization of the logarithmic sum of the success probability M_k for packets generated by node k, which aims at the proportional fairness in terms of utility M_k for node k over all nodes. It also means the maximization of the success probability of delivery for all the packets if the packet losses occur independently.

In the following, we explain how the proposed method derives a slot allocation in case of network topology with $n = 8$ nodes. Fig. 2a shows an example of slot allocation on the left side of the separated link of 3-5 model. In this example, the packet generation rates of nodes A, B, C are $1, 3, 2$, respectively. The expressions a_j, b_j and c_j are the numbers of slots allocated to transmit a packet generated by nodes A, B and C, on link j, respectively. The success probability of delivery for packets generated by node A, B, and C are denoted by M_a, M_b and M_c, respectively, and can be calculated as follows.

$$M_a = (1-q_1^{a_1})^{r_1}, \quad M_b = (1-q_1^{b_1})^{r_2}(1-q_2^{b_2})^{r_2} \tag{1}$$

$$M_c = (1-q_1^{c_1})^{r_3}(1-q_2^{c_2})^{r_3}(1-q_3^{c_3})^{r_3} \tag{2}$$



(a) Transmission scheduling on 3 nodes.

(b) Transmission scheduling on 5 nodes.

Fig. 2: Transmission scheduling on 3 nodes (left) and 5 nodes (right).

Here, q_j is the packet loss rate of link j and r_i is the packet generation rate of node i. Then the maximization problem is defined as follows.

$$\max M_a M_b M_c \quad \text{subject to} \quad r_1 a_1 + r_2 b_1 + r_2 b_2 + r_3 c_1 + r_3 c_2 + r_3 c_3 = T \tag{3}$$

The Lagrangian multiplier is applied to a relaxation version of equations (3) to derive equations (4) - (6) where a_i, b_i, c_i are not restricted to natural numbers.

$$a_1 = b_1 = c_1 = -\frac{\log(1-\alpha\log(q_1))}{\log(q_1)} \tag{4}$$

$$b_2 = c_2 = -\frac{\log(1-\alpha\log(q_2))}{\log(q_2)}, \quad c_3 = -\frac{\log(1-\alpha\log(q_3))}{\log(q_3)} \tag{5}$$

$$(r_1 + r_2 + r_3)a_1 + (r_2 + r_3)b_2 + r_3 c_3 = T \tag{6}$$

α can be determined by Equation (4)-(6). Hence, the real value solution for (4)-(5) can be derived from α. However, the real value solution of the relaxed problem cannot be used for the static slot allocation. Therefore, we examine integer value solutions near the derived real value solution to seek the optimal integer value solution that maximizes the original problem. Note that the real value solution of the relaxed problem can provide an upper-bound of the objective function $M_a M_b M_c$.

With a more complex manner, the equations can also be derived for the 5 node part on the right side of the 3-5 model. In the case of 5 nodes, simultaneous packet transmissions by two distant nodes in the same time-slot is possible when the interference avoidance condition is cleared. Fig. 2b shows a slot allocation on the right side of the separated link. In this example, the packet generation rates of nodes H, G, F, E, D are $1, 2, 3, 2, 1$, respectively.

The formulation of the optimal slot allocation problem is as follows.

$$M_d = (1-q_5^{d_5})^{r_4}(1-q_6^{d_6})^{r_4}(1-q_7^{d_7})^{r_4}(1-q_8^{d_8})^{r_4}(1-q_9^{d_9})^{r_4} \tag{7}$$

$$M_e = (1-q_6^{e_6})^{r_5}(1-q_7^{e_7})^{r_5}(1-q_8^{e_8})^{r_5}(1-q_9^{e_9})^{r_5} \tag{8}$$

$$M_f = (1-q_7^{f_7})^{r_6}(1-q_8^{f_8})^{r_6}(1-q_9^{f_9})^{r_6} \tag{9}$$

$$M_g = ((1-q_8^{g_{8'}})(1-q_9^{g_9+g_{9'}}) + (1-q_8^{g_8})(q_8^{g_{8'}})(1-q_9^{g_9}))^{r_7} \tag{10}$$

$$M_h = (1-q_9^{h_9+h_{9'}})^{r_8} \tag{11}$$

Here, $g_{8'}$, $g_{9'}$ and $h_{9'}$ represent the number of slots allocated to transmit a packet in the simultaneous transmission region in which the interference avoidance condition is cleared. Because of the nature of the model, simultaneous transmissions are possible on a pair of links $j = (5,8)$ or another pair of links $j = (6,9)$.

$$\max M_d M_e M_f M_g M_h \tag{12}$$

$$\text{subject to} \quad r_4 d_5 + r_4 d_6 + r_4 d_7 + r_4 d_8 + r_4 d_9 + r_5 e_6 + r_5 e_7 + r_5 e_8 + r_5 e_9 + r_6 f_7 + r_6 f_8 + r_6 f_9 + r_7 g_8 + r_7 g_9 + r_8 h_9 = T \tag{13}$$

$$r_4 d_5 = r_7 g'_8, \quad r_5 e_6 + r_4 d_6 = r_8 h'_9 + r_7 g'_9 \tag{14}$$

In a similar way in the previous 3 node case, the real value solution of the relaxed problem is derived and then the optimal integer value solution of the original problem can be found.

3 Simulation

To validate the effectiveness and the issues of the scheduling proposed in the previous section, we conduct synthetic simulations using an advanced packet-level network simulator, Scenargie, that can reflect various wireless configurations and realistic environments. The probability of delivering all packets (from all nodes) within one cycle period is considered as performance metric presented by three different values. Theoretical upper-bound (TUB) value means the theoretical maximum value of the objective function obtained by solving the relaxed version of the maximization problem. Model-based computed (COM) value means the computed probability of delivering all packets according to a slot allocation using an optimal integer-value solution of the original integer-constraint maximization problem. Simulation-based measured (MES) value means the measured ratio of the number of successfully delivered packets to all packets in simulation. Similarly the success delivery probability for the packets generated by each specific node is examined by the three different values.

3.1 Simulation Settings

Simulations are executed in three cases with different settings for each link and node assuming the number of nodes n is 8.

- Case1 : High packet loss rate near each GW.
- Case2 : High packet loss rate and high packet generation rate at the left side of the sensor array.
- Case3 : High packet loss rate at the right side of the sensor array and high packet generation rate at the left side of the sensor array.

The information of link and node is shown in Tables 1 and 2.

Table 1: Packet loss rate of each link

Case	q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9
1	0.4	0.1	0.2	0.2	0.4	0.2	0.2	0.1	0.4
2	0.5	0.3	0.4	0.4	0.2	0.3	0.2	0.1	0.3
3	0.3	0.1	0.2	0.3	0.3	0.4	0.4	0.2	0.5

Table 2: Packet generation rate of each node

Case	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8
1	3	2	1	2	2	1	3	1
2	2	3	3	1	1	2	1	2
3	2	3	3	1	1	2	1	2

Table 3: The wireless link settings of Scenargie

Wireless standard	802.11g
Transmission power	20[-dbm]
Received power	-100[dbm]
Modulation type	BPSK0.5

Table 4: The relationship between the node distance and the packet loss rate

Loss rate	0.1	0.2	0.3	0.4	0.5
Distance[m]	938.00	954.75	964.55	974.19	983.45

The wireless link settings of Scenargie are shown in Table 3. Each node does not use automatic repeat-request (ARQ) and carrier sense by ACK but adopt broadcast transmission. Three different values ($T = 50$, $T = 75$, $T = 100$) are used as the number of slots in one cycle. The relationship between the node distance and the packet loss rate on the link is obtained in the following manner by Scenargie; the CBR application transmits packets 10000 times between the two nodes without any interference from other communications; then the packet loss rate is decided by averaging the measured values over 10000 simulation instances.

Table 4 shows the relationship between the node distance and the packet loss rate on link measured on Scenargie.

3.2 Simulation results

Fig. 3 shows the slot allocation of the right part of 3-5 model at the number of slots $T = 75$ in Case 2. The number beside the arrow indicates how many times the packet is sent on the current link. Nodes G and H are transmitting simultaneously.

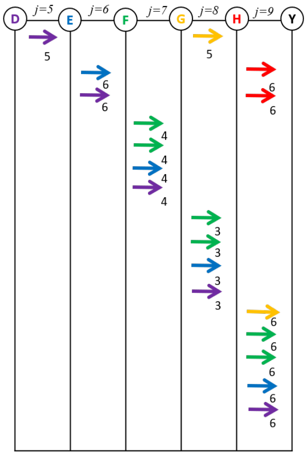


Fig. 3: The slot allocation of the right part of 3-5 model with slots $T = 75$ in Case 2

Fig. 4 shows the total packet delivery ratios of all cases ($T = 75$). I, II and III in the figure show TUB value, COM value, MES value. The blue bar graph shows the total packet delivery ratios of 4-4 model and the red bar graph shows the total packet delivery ratios of 3-5 model.

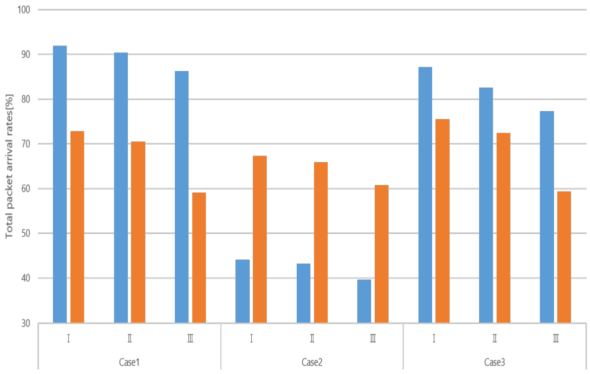


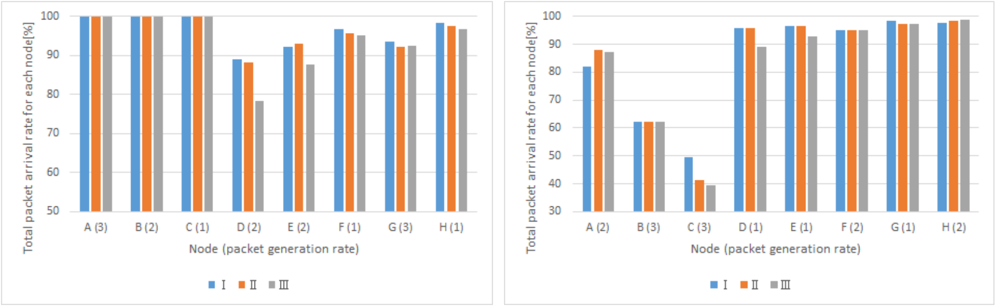
Fig. 4: The total packet delivery ratios

Case 1 gets higher total packet delivery ratio of 4-4 model than 3-5 model in all of TUB value, COM value, and MES value. The difference in packet loss rates between the left and right sides separated by the link $j = 5$ is small, and the minimum number of transmissions when considering the packet generation rate of each node is close between the left and right sides. As a result, the total packet delivery ratio of the 4-4 model becomes high.

Case 2 gets higher total packet delivery ratio of 3-5 model than 4-4 model in contrast to Case 1. The packet loss rate on the left side and the packet generation rate of each node are high with the link $j = 4$ as a boundary. However, since the 3-5 model can reduce the number of hops of packets exchanged on the left side, the 3-5 model achieves a higher total packet delivery ratio than the 4-4 model. The fact that a node having a high packet generation rate is not arranged near the upstream of the right side portion also contributes to this delivery ratio. When a large number of nodes with a high generation rate are arranged upstream of a flow, it is necessary to transmit all different packets of the nodes for each hop, and as a result, a finite number of slots is compressed. It is considered appropriate not to arrange a large number of nodes having a high packet generation rate near the separation point.

Case 3 gets higher total packet delivery ratio of 4-4 model than 3-5 model. This result follows from the fact that weight of the overall packet generation rate and the weight of the packet loss rate are not biased to one.

The success delivery probability for all packets degrades in order of TUB value (I), COM value (II), and MES value (III) in all cases. It is natural that COM value is always lower than TUB value because TUB value is the theoretically maximum value of the objective function allowing a real-number solution and COM value is a value of the same objective function with an optimal integer-number solution that generally differs from the real-number optimal solution. Furthermore, MES value in simulation is always lower than COM value since an interference of simultaneous transmissions actually happens around the separation link between the most upstream nodes of the left-side and right-side flows.



(a) Case 1, 3-5 model, $T = 75$

(b) Case 2, 3-5 model, $T = 50$

Fig. 5: Total packet delivery ratios for each node

Fig. 5 shows the relationship between the total packet delivery ratio and the packet generation rate of each node. The packet generation rate of each node is indicated in parenthesis. As shown in the figures, the total packet delivery ratios of the upstream nodes are generally lower than those of the downstream nodes. This is because the packets generated by a node at upper-side should traverse more number of lossy links. However, node G in Fig. 5a shows an exception. The total packet delivery ratio of node G, whose packet generation rate is higher than upstream node F, is lower than that of node F. In addition, nodes B and C in Fig. 5b suffer from significantly low total packet delivery ratios compared with the nodes D to H in the right-hand side despite that the link loss rates are not very different from the left-hand side. This comes from our slot allocation policy. It aims to maximize the probability of delivering all packets from all nodes without distinguishing between different packets generated by the same node and different packets generated by different nodes. Assuming that each generated packet has the delivery probability of around x, the total packet delivery ratio of a node with the packet generation rate of m is around x^m, which decreases as m increases.

4 Concluding Remarks

In this paper, we considered a TDMA-based packet transmission scheduling for tandemly-connected sensor networks with lossy links. We have enhanced our previous work to derive a static time-slot allocation maximizing the success delivery probability for packets, even if the packet generation rates are heterogeneous over nodes. As future work, we introduce an inter-packet XOR coding in transmitting multiple packets by multiple times, which was shown to be beneficial [6] but is not trivial in our case of heterogeneous packet generation rates.

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