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journal or publication title	2020 International Conference on Information Networking (ICOIN)
year	2020-03-02
URL	http://hdl.handle.net/10228/00007972

doi: http://dx.doi.org/10.1109/ICOIN48656.2020.9016551

Scheduling for tandemly-connected sensor networks with heterogeneous link transmission rates

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***Abstract*—As a simplest sensor network topology, a tandemly-connected multi-hop wireless network model is studied, in which nodes are tandemly arranged and serially connected by unreliable lossy links. Each node generates a data packet in every one cycle period and forwards it bounded for either of two gateways at both ends of the network; the gateways can send the data to a server using a loss-free infrastructure. In such environments, packet losses often happen due to not only attenuation and fading but also interference among links, thus unscheduled packet forwarding schemes are inefficient and suffer from a low success ratio of packet delivery to the server. In our previous paper, we proposed a centralized scheduling to design a static time-slot allocation for redundant packet transmission based on the positions and packet loss rates of links to maintain a high success probability of delivering all sensor data. However, it only considered homogeneous links with the same transmission rate, and also it is not optimal in some topological conditions. Therefore, in this paper, we essentially enhanced it to adapt to heterogeneous links with different transmission rates and to topological conditions that are not covered by the previous scheme. Our scheme analytically derives an optimal static time-slot allocation and combines it with forward erasure correction (FEC) against packet losses based on inter-packet XOR coding. The results of synthetic simulation have shown the validity of the analytical optimization, the benefit of coding, and the issues hard to consider in analytical models as well.**

***Index Terms*—Multi-hop wireless communications, packet transmission scheduling, link transmission rate, packet loss rate**

I. Introduction

Multi-hop wireless networks have attracted much attention for a few decades due to their lower cost, rapid deployment, and flexibility in connecting or covering nodes in an area where single-hop wireless networking is not sufficient to work. In particular, to monitor a large elongated area and collect those data by a server in case that a communication infrastructure is unavailable or too costly, multi-hop wireless networks are commonly used in the wild. However, in such environments, packet losses likely happen due to attenuation/fading on each link as well as transmission conflicts among links. In general, lost packets are recovered in either a proactive manner, e.g., redundant transmission with Forward Erasure Correction (FEC) or a reactive manner, e.g., Automatic Repeat-reQuest (ARQ). Simultaneous transmissions are avoided as Media Access Control in either a scheduling-based manner, e.g., Time Division Multiple Access (TDMA) or a contention-based manner.

This work deals with the simplest topology of multi-hop wireless networks where stationary nodes are tandemly arranged and serially connected by unreliable lossy links as illustrated in Fig. 1. Each node is a data sender (it generates a data packet in every cycle period) as well as a data forwarder (it relays a packet with redundant transmissions bounded for an edge of the tandem network). Two gateways are located at the both edges of the network and connected with a single central management server via a loss-free network. Our work is motivated by real facility monitoring scenarios (e.g., along a road, a river, or a series of towers). For example, to check the facility safety and health of power transmission towers (electricity pylons) arranged in tandem over a long distance, monitoring sensors are installed at each tower and wirelessly connected each other between towers. Each sensor node periodically generates a packet of monitoring data, which should be eventually bounded for a single central management server. Each packet can be exchanged only between two neighboring nodes by a limited distance, low-cost and lossy unreliable wireless link, while a whole network structure is stable. Note that, on general topologies, a huge number of studies have focused on the control of packet flows in time (i.e., scheduling) and space (i.e., routing or frequency band assignment) to avoid interferences among simultaneous transmissions. The conflict graph is commonly used there to describe an interference situation among links [1]; however, they are often too complex to exactly derive an optimal schedule and/or routing. In contrast, on tandem topologies, the path model for routing and the conflict graph can be handled easier, which allows a simpler formulation for optimization in both scheduling and routing.

In our previous work [2], we proposed a centralized framework of packet transmission scheduling for tandemly-connected sensor networks, consisting of a static time-slot allocation scheme over all links and a packet forwarding scheme over allocated slots at each link. The time-slot allocation is based on the dual separated (DS) path model to consider positions, an identical transmission rate, and (time-averaged) loss rates of links that are assumed to be known. The calculated slot allocation is optimal in the sense that it theoretically maximizes the success probability of delivering all packets under the condition that each packet to be forwarded is redundantly transmitted multiple times according to the slot allocation on a DS path model.

However, our previous work is applicable only for homogeneous links with the same transmission rate. Furthermore, the DS path model is not optimal in some cases. In this paper, therefore, an enhanced scheme is developed to adapt to heterogeneous links with different transmission rate and to topological conditions that are not covered by the previous scheme.

II. Related works

Two fundamental issues in multi-hop wireless networks are the lossy unreliable wireless radio links and the conflicts (interferences) among simultaneous transmissions on adjacent links (or links within an interference range) using the same radio frequency channels [3], in using omnidirectional antenna.

Ho [4] studied multi-hop lossy wireless networks and proposed an online and distributed scheduling policy to provide hard end-to-end delay guarantees by deriving a sufficient condition to be feasible. Sagduyu, et al. [5] implemented network coding in tandem network case with wireless queuing networks. In earlier work of TDMA scheduling, a randomized time slot scheduling algorithm, called DRAND was proposed [6]. On the other hand, the shortest schedules are proposed in [7], which introduced two centralized algorithms. Zeng, et al. [8] proposed a new scheduling algorithm based on the collaboration of nodes to resolve the slot collision when nodes try to assign slots to them. Tokito, et al. [9] dealt with TDMA-based wireless mesh networks with multiple gateway nodes and proposed a spanning tree construction algorithm to maximize the traffic volume transferred between the mesh network and the central server via gateways. Chaporkar, et al. [10] considered a simple distributed scheduling strategy (the maximal scheduling), and analytically showed a guaranteed fraction of the maximum throughput region by the maximal scheduling in arbitrary wireless networks. On the other hand, our work focuses on a centralized TDMA scheduling on tandem topology with two gateways at the edges to theoretically maximize the success delivery ratio of all packets in one cycle period; which has not been well studied.

III. System Model

This study assumes tandemly-connected multi-hop wireless sensor networks as illustrated in Fig. 1. The sensor nodes and links are numbered separately from the left to the right (starting from 1). Let n be the number of nodes; let b_j and q_j be the transmission rate and the time-averaged packet loss rate on link j ($j = 1, 2, \cdots, n+1$), respectively.

- Each link is lossy and half-duplex; a packet transmission at a node affects both links connected to the node (e.g., with omnidirectional antenna); the link layer does not provide any ARQ and transmission power adaptation.
- Each node generates a packet every cycle period of D which should be delivered to server S via either the gateway X or Y; a network between S and X or Y is loss-free.
- Each node acts as relay in a store-and-forward manner; it stores packets from an upstream node and redundantly sends them to a downstream node at scheduled slots.
- S knows transmission rates b_j and time-averaged loss rates q_j of each link j; S derives a global time-slot allocation based on them so as to fully utilize the bandwidth of all links while avoiding the transmission interference among adjacent links; and then installs the slot allocation (schedule) to each node.

Hence the problem is how to deliver a packet generated at each node to either the gateways X or Y along the lossy links during a cycle period of D with a high success probability and fairness among packets from different nodes.

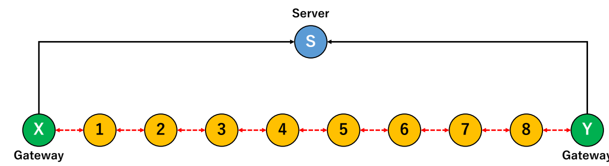


Fig. 1: Example topology of this research

IV. Proposed Method

The proposed packet transmission scheduling is performed in the following steps. On the routing (i.e., the packet transmission direction on each link), all reasonable **path models** are considered. On a given path model, an optimal static time-slot allocation is derived by computing the theoretical probability that all n packets are successfully delivered to the server in case of using **the basic redundant-transmission scheme**. In deriving the slot allocation, a static interference avoidance policy based on **the communication distance** is considered. All path models are examined one by one with each optimal slot allocation and then a best combination of path model and slot allocation is selected in terms of maximizing the above success delivery probability. Note that, for actual packet transmission at each node, **the coded redundant-transmission scheme** is used instead of **the basic redundant-transmission scheme** which significantly increases the success delivery probability.

A. Path model

Two classes of path models, the dual separated (**DS**) path model and the single branched (**SB**) path model, are considered. In DS path model, two independent paths are separated at a separation (unused) link. Any node at the left of the separation link will send packets to the left direction; and any node at the right of the separation link will send to the right. It is also 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 SB path model, a branched path is started from a single source node (i.e., a central node). The central node will send packets to both directions; any node at the left of the central node will send to the left direction; and any node at the right of the central node will send to the right. It is also called l-1-r model where l and r are the number of nodes at the left and the right of the central node, respectively.

In an example topology illustrated in Fig. 1, there are 7 candidates as the separation link for DS path model. For example, if link between nodes 3 and 4 is the separation link, the path model is 3-5 model. On the other hand, there are 8 candidates as the central node for SB path model. For example, if node 3 is the central node, the path model is 2-1-5 model.

B. Time-slot allocation

Let B be the least common multiple of all link transmission rates $\{b_j\}$ and L be the packet size; then $U = L/B$ is the unit time (i.e., time duration of one slot) and $T = D/U$ is the total number of available slots in one cycle. On link j, it takes $T_j = B/b_j$ slots to transmit one packet; a high transmission rate link may need only one or two slots but a low transmission rate link needs much more slots. Let $s_{i,j}$ be the number of redundant transmissions on link j scheduled for a single packet generated at node i. For $s_{i,j}$ transmissions, $T_j \times s_{i,j}$ slots should be allocated on link j. Fig. 2 illustrates the relationship of the parameters in an example of slot allocation in the left side of 3-5 model.

To describe global slot allocation precisely, we define $\mathcal{A} = \{(i,j)|s_{i,j} \geq 1\}$, which is a set of (a source node of packets, a link used by those packets) pair that directly reflects the path model (Section IV-A). Furthermore, since simultaneous transmissions on multiple links are allowed if they do not conflict with each other, we should consider an additional notation explained later.

In this paper, **the communication distance-based** interference avoidance policy is used to restrict simultaneous transmissions in the same direction among multiple nodes as follows. In a given direction, suppose node j is located downstream from node i and assume the communication distance (i.e., the radio wave interference range) R of node j is known. When node i transmits a packet to a downstream adjunct node k, if the distance between nodes k and j is larger than R, this transmission is not affected by the transmission by node j. This is still simple but more realistic compared with the hop-based interference avoidance in the previous scheme.

The simultaneous transmissions among multiple nodes follow this rule. For example, in Fig.3b (Case2, 3-5 model), a packet generated at node 7 (indicated by blue) can be transmitted to node 8 through link 8 in two different time-stages; the early one is at the beginning of the cycle when node 4 also performs packet transmission simultaneously. The possible late stage for the packet indicated by blue is a period after node 7 has received packets forwarded by node 6. The number of possible transmissions at the early stage is denoted by $s'_{7,8}$ and that of the late (normal) stage by $s_{7,8}$ ($s'_{7,8} = 2$ and $s_{7,8} = 0$ in this example). In the same way, multiple stages on link 9 are described by $s'_{7,9} = 3$ and $s_{7,9} = 0$ (blue arrows), and by $s'_{8,9} = 2$ and $s_{8,9} = 0$ (red arrows). Note that, in this particular example, the number of stages is actually one; but generally both $s_{8,9}$ and $s'_{8,9}$ can be positive. For sake of simplicity, we consider at most two stages and use notation s and s' in this paper. Thus set $\mathcal{A}' = \{(i,j)|s'_{i,j} \geq 1\}$ is used to define the early stage transmission in addition to $\mathcal{A}$, and the set of all variables (variable names) to represent a global slot allocation pattern is denoted by $\mathcal{V} = \{s_{i,j}|(i,j) \in \mathcal{A}\} \cup \{s'_{i,j}|(i,j) \in \mathcal{A}'\}$; the number of all variables is $K = |\mathcal{V}|$. Set $\mathcal{V}$ exactly represents the path model (Section IV-A) and the interference avoidance policy.

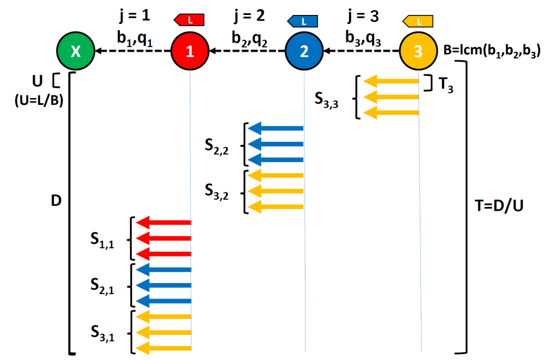


Fig. 2: Example slot allocation in the left side of 3-5 model

Slot allocation σ is defined as a map from $\mathcal{V}$ to $\mathcal{N}^K$ where $\mathcal{N}$ is the set of positive natural numbers. The set of all possible slot allocations on $\mathcal{V}$ is denoted by $\Sigma_{\mathcal{V}}$. The goal of slot allocation is to successfully deliver all packets generated at all nodes in the cycle to the central server along the lossy links as much as possible during the cycle period of D (i.e., T slots in total) with a fairness among packets. Therefore we calculate a slot allocation based on an optimization problem. Let $M_i(\sigma)$ be the probability that a packet generated at node i is successfully delivered to either gateway X or Y assuming packet loss events on different links are independent each other. For given slot allocation pattern $\mathcal{V}$ depending on the path model, let $\overline{M}(\sigma)$ be $\prod_{i=1}^{n} M_i(\sigma)$; and then the optimization problem is defined by:

$$\max_{\sigma \in \Sigma_{\mathcal{V}}} \overline{M}(\sigma) \;\text{ subject to conditions on } (\sigma, T). \quad (1)$$

Note that the objective function $\overline{M} = \prod_i M_i$ can be interpreted in two ways. If packet loss events on each link are independent of source node i of the packet, $\overline{M}$ equals the probability that all n packets successfully reach the server. On the other hand, if M_i can be considered as utility of σ for node i, a σ maximizing $\overline{M}(\sigma)$ realizes the proportional fairness among all n nodes. By solving the problem (1), we get slot allocation $\sigma^*(\mathcal{V})$ as solution. By getting $\sigma^*(\mathcal{V})$ for each possible slot allocation pattern $\mathcal{V}$ and comparing $\overline{M}(\sigma^*(\mathcal{V}))$, we can finally select the best one, i.e., slot allocation pattern $\mathcal{V}^*$ and slot allocation $\sigma^*(\mathcal{V}^*)$.

In the following part, how to solve the problem (1) for l-1-r path model is explained through an example shown in Fig. 3c (this is an optimal slot allocation in Case3, 3-1-4 model). In this example, $\mathcal{V} = \{s'_{1,1}, s_{2,1}, \ldots, s_{4,4}, s_{4,5}, \ldots, s'_{7,8}, s_{6,8}, \ldots, s_{4,9}\}$. Note that $s'_{8,9} = 0$ and thus $s'_{8,9}$ is not in $\mathcal{V}$ due to the interference avoidance policy explained before. In addition, since a particular $\mathcal{V}$ is assumed here, it is omitted in the following notations. Except for M_4, M_i has a simple form such as $M_1 = 1 - q_1^{s'_{1,1}}$, $M_2 = (1 - q_1^{s_{2,1}})(1 - q_2^{s_{2,2}})$, and $M_8 = 1 - q_9^{s_{8,9}}$. If the slot allocation pattern includes multiple stages, M_1, M_7, and/or M_8 will be more complex but can be handled in a similar way [2]. On the other hand, M_4 has a new form because node 4 multicasts a packet to both directions that is the essential difference from l-r path model.

$$M_4 = M_4^{(l)} + M_4^{(r)} - M_4^{(l)} M_4^{(r)}$$

where $M_4^{(l)} = (1-q_1^{s_{4,1}})(1-q_2^{s_{4,2}})\cdots(1-q_4^{s_{4,4}})$ and $M_4^{(r)} = (1-q_5^{s_{4,5}})(1-q_6^{s_{4,6}})\cdots(1-q_9^{s_{4,9}})$.

The constraint conditions between σ and T in (1) are:

$$\begin{aligned} T &= T_4 s_{4,4} + T_3(s_{3,3}+s_{4,3}) + T_2(s_{2,2}+s_{3,2}+s_{4,2}) \\ &\quad +T_1(s_{2,1}+s_{3,1}+s_{4,1}), \\ &= T_5 s_{4,5} + T_6(s_{4,6}+s_{5,6}) + T_7(s_{4,7}+s_{5,7}+s_{6,7}) \\ &\quad +T_8(s_{4,8}+s_{5,8}+s_{6,8}) + T_9(s_{4,9}+\cdots+s_{7,9}+s_{8,9}), \end{aligned}$$

$$T_1 s'_{1,1} \quad = \quad T_4 s_{4,4} = T_5 s_{4,5} = T_8 s'_{7,8} \qquad (2)$$

To apply Lagrange multiplier method to (1) subject to (2), we consider a relaxed problem on real numbers and then obtain the following equations to represent $s_{i,j}$ including four unknown positive real numbers $\alpha, \beta, \gamma, \delta$ as interim variables:

$$s_{i,j} \quad = \quad -\log\left(1 - \frac{X}{T_j}\log q_j\right) / \log q_j \qquad (3)$$

where X is replaced by α for $i = 1,2,3,\ j = 2,3$; by β for $i = 4,\ j = 1,2,3,4$; by γ for $i = 4,\ j = 5,6,7,8,9$; and by δ for $i = 5,6,7,8,\ j = 5,6,7,8,9$.

Then we test natural number $m = 1, 2, \ldots$ so as to find a solution assuming $m = T_4 s_{4,4} = T_5 s_{4,5}$. For given m, equations (2) and (3) have either a unique solution $(\alpha, \beta, \gamma, \delta)$ or no solution (infeasible). If exists, $(\alpha, \beta, \gamma, \delta)$ can be numerically solved and thus $s_{i,j}$ in real numbers can be computed from (3). Accordingly, we can find a best $m = m^*$ and an optimal real number slot allocation $\tilde{\sigma}^* = \tilde{\sigma}(m^*)$:

$$\tilde{\sigma}(m) = \arg\max_{\sigma \in \tilde{\Sigma}(m)} \overline{M}(\sigma), m^* = \arg\max_m \overline{M}(\tilde{\sigma}(m)),$$

where $\tilde{\Sigma}(m)$ is the set of all possible relaxed slot allocations in $(\mathcal{Z}^+)^K$ with condition $m = T_4 s_{4,4} = T_5 s_{4,5}$ ($\mathcal{Z}^+$ is the set of positive real numbers). Finally, we define Σ^{*-} as the set of natural number slot allocations most close to given $\tilde{\sigma}^*$ (all σ in Σ such that the difference from $\tilde{\sigma}^*$ in any variable $s_{i,j}$ does not exceed one), and find an optimal slot allocation σ^* as a best one in Σ^{*-}.

C. Packet transmission on allocated slots

Two transmission schemes against packet losses are considered for a node to forward packets either generated by itself or received from an upstream node. One is **the basic redundant-transmission scheme** in which each packet (generated by node i) is individually transmitted on link j in $s_{i,j}$ times at the slots allocated to the packet. Each node transmits its possessed packets 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 pack is used for the next packet.

The other is **the coded redundant-transmission scheme** in which each "original packet" (either generated by itself or received from an upstream node) at a node is comprehensively transmitted multiple times using an inter-packet composition by XOR coding at all allocated slots. Coding and decoding are performed at each node. Suppose the right-to-left transmission where node j should forward its possessed packets to node $(j-1)$ on link j. A random XOR coding is used to make the necessary number of coding packets from all original packets possessed at node j. Let $n^{(left)}$ be the index of the most upstream node in this right-to-left transmission; then the total number of possible transmissions for coded packets on link j is $\bar{s}_j = \sum_{i=j}^{n^{(left)}} s_{i,j}$.

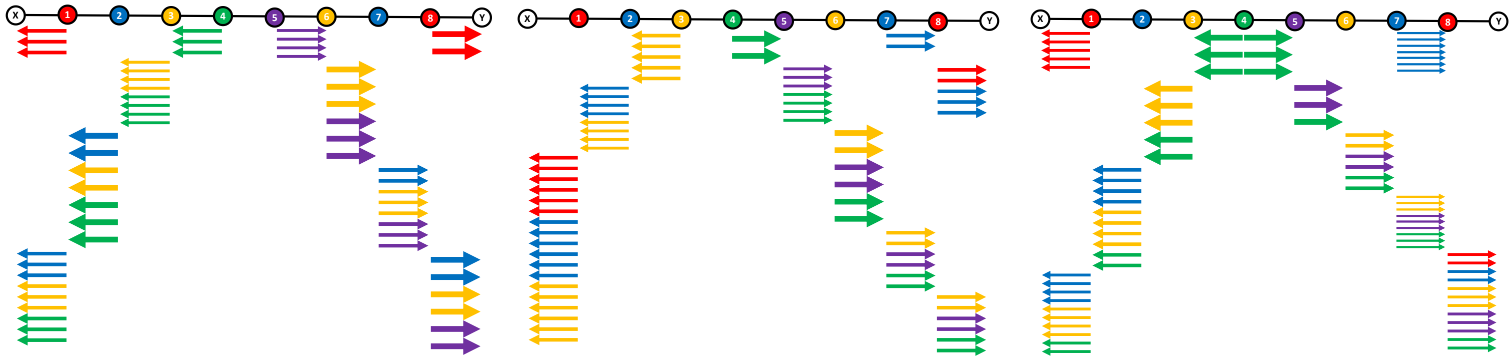
Each coded packet is an XOR combination of original packets; and node j transmits the number $\bar{s}_j$ of coded packets by selecting combinations randomly but equally over all original packets to be forwarded. To do so, node j has its coding table (CT_j) in which all combinations of original packets possibly possessed at node j are listed with each used-flag to indicate that a combination is already used (transmitted) or not. CT_j is determined in advance based on the calculated slot allocation σ in Section IV-B. Let $k = n^{(left)} - j + 1$ be the number of possible possessed original packets ; the number of all combinations is $2^k - 1$. For the equality (fairness) among original packets, variable $c_{i,j}$ is also used to represent virtual transmission times on link j for the packet generated by node i by counting the contribution of coded packets transmissions.

The online coding and transmission algorithm at node j is as follows. At the random selection of a combination from CT_j, the following three conditions are checked. The combination should NOT (i) include any unpossessed original packet; (ii) be used before (used-flag should be off); and (iii) include any original packet i that has already been virtually transmitted more that $s_{i,j}$ times (i.e., $c_{i,j}$ should be $\leq s_{i,j}$). If all conditions are satisfied, the coded packet is encoded and transmitted. The used-flag of the selected combination is on, and virtual transmission counter $c_{i,j}$ for each packet i included in the combination is updated: $c_{i,j} = c_{i,j} + 1/r$, where r is the number of original packets included in the selected combination. Otherwise, the random selection is retried. If the number of original packets is small but $\bar{s}_j$ is large, all combinations may become used. In such cases, after resetting all used-flags, the coding and transmission will continue.

V. SIMULATION EVALUATION

In simulation, we used Scenargie, a simulation software which can adapt to various wireless configurations and real environments. The results of three synthetic cases are examined to evaluate the proposed scheme. In Case1, link loss rates are not high and similar over all links. In Case2, lossy links are arranged at the left edge portion (near to GW X). In Case3, two adjunct links at the central portion are highly lossy.

In this simulation, the essential parameters (the time-averaged loss rate q_j, the transmission rate b_j) of link j are



(a) Case1 4-4model

(b) Case2 3-5model

(c) Case3 3-1-4model

Fig. 3: Calculated Schedule

determined by the distance between two nodes at the ends of the link and the modulation scheme used on the link. The relationship between the distance and those parameters in each modulation scheme is estimated in preliminary simulation. The average value of the loss rate and the transmission rate is measured by transmitting $10,000$ packets in a single-hop setting without any interference in each corresponding condition. Let $\tilde{b_j}$ be this pre-estimated transmission rate. As shown in Section IV-B, $T_j = B/b_j$, i.e., the number of time-slots required to transmit one packet, is essential to calculate the slot allocation. However, the actual time (the actual number of slots) taken to transmit one packet in real simulation is sometimes larger than that estimated in preliminary simulation, i.e., $\tilde{T_j} = B/\tilde{b_j}$. This is because some degree of interference happens more or less in real simulation for multi-hop setting. This means, if we use $\tilde{T_j}$ to calculate a slot allocation, a packet transmission in the allocated slots may not complete in time and the next packet transmission will be delayed. This delay will be accumulated and eventually cause an interference with neighboring nodes' transmissions that will start in time according to the given schedule, by which the actual loss rate in real simulation becomes larger than the pre-estimated loss rate measured in preliminary simulation. Therefore, to avoid unexpected high loss rates and an improper slot allocation, a 80% of the pre-estimated $\tilde{b_j}$ is used as the effective transmission rate to calculate the slot allocation for real simulation.

The parameter set for each link are shown in Table I including loss rate (top), distance [L:Long, M:Medium, S:Short](middle), and transmission rate [Mbps] (bottom) in Cases 1, 2, and 3. "Transmission rate" represents the effective transmission rate used in the calculation, and the pre-estimated transmission rate is shown in parentheses. The parameters L and D in IV-B are $L = 500$ [byte] and $D = 0.02$ [sec], i.e., the data generation rate at each node is 200k [bit/sec].

Figure 3 shows the calculated optimal slot allocation for the best path model in each Case. For packet transmissions in the same direction (to the left or the right), the same color arrows represent packets generated at the same node, the number of arrows represents the number of transmissions,

	$q1$	$q2$	$q3$	$q4$	$q5$	$q6$	$q7$	$q8$	$q9$
C1	0.2	0.1	0.3	0.1	0.2	0.3	0.2	0.1	0.1
	M	L	S	M	M	S	L	M	L
	5.8 (7.2)	4.0 (5.0)	7.9 (9.8)	5.8 (7.2)	5.8 (7.2)	7.9 (9.8)	4.0 (5.0)	5.8 (7.2)	4.0 (5.0)
C2	0.4	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.1
	M	S	M	L	L	M	L	M	M
	5.8 (7.2)	7.9 (9.8)	5.8 (7.2)	4.0 (5.0)	4.0 (5.0)	7.9 (9.8)	4.0 (5.0)	5.8 (7.2)	5.8 (7.2)
C3	0.3	0.4	0.2	0.6	0.6	0.1	0.2	0.3	0.2
	S	M	L	L	L	L	M	S	S
	7.9 (9.8)	5.8 (7.2)	4.0 (5.0)	4.0 (5.0)	4.0 (5.0)	4.0 (5.0)	5.8 (7.2)	10.6 (13.2)	7.9 (9.8)

TABLE I: Parameters for each link

and the thickness of the arrow represents the time required for transmission.

Fig.4 compares the theoretical values of the probability of success delivery achieved by optimal slot allocations on some path models and the actually measured values of that in simulation. From the theoretical values, 4-4, 3-5 (**DS** type), and 3-1-4 (**SB** type) are the best path models in Cases 1, 2, and 3, respectively. On the other hand, from the measured values, 3-1-4, 3-5, and 3-1-4 are the best path models. First, a **DS** type path model is best in some case and a **SB** type path model in another case. This clearly supports the necessity of the newly introduced **SB** path model. The reason for optimality of 3-1-4 model in Case 3 may be its consecutive highly lossy links at the center. In such cases, on DS type path model, even if a highly lossy link is assigned to the separation link and is not used, an adjunct highly lossy link should take on the responsibility to transmit the most upstream node's packets.On the other hand, on SB type path model (3-1-4 in this case), the two central links can share the responsibility to transmit those packets, which may increase the probability of success delivery of all packets.

Second, at least in Cases 2 and 3, the best path model selected by the theory is consistent with that measured in simulation. This validates the correctness and usefulness of the proposed optimal scheduling scheme.

Third, the inconsistency in the best path model selection by theory (4-4) and simulation (3-1-4) in Case 1 suggests a weakness of DS type path model. Fig. 5 shows the loss rate of each link: the pre-estimated value (used as setting

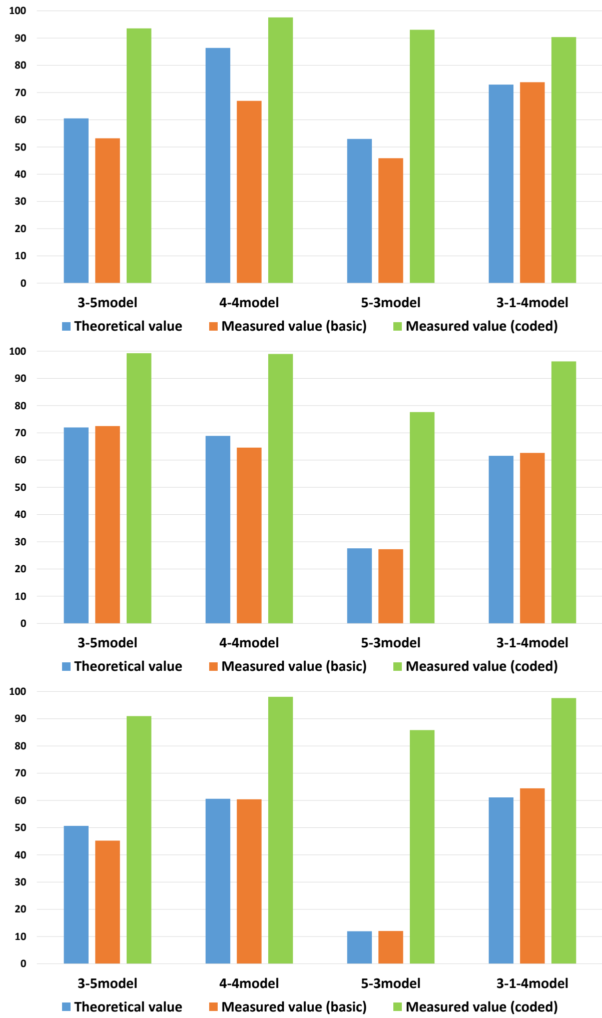


Fig. 4: Probability of Success Delivery in Case1 (top), Case2 (middle), Case3 (bottom)

parameter of simulation) and the measured. The measured loss rates increase at the links near to the separation link in DS path models. This is because the interference among packet transmission in opposite directions around the separation link is not considered in calculating the slot allocation. Hence, if the distance of the separation link is short (M of Table I in this case), two neighboring most upstream nodes may suffer from packet losses by interference.

Finally, by comparing the measured value with the basic redundant transmission (basic) and that with the coded redundant transmission (coded) in each case in Fig.4, the benefit of the coded scheme is clearly demonstrated. In Case3, while 3-1-4 model is superior if confining the redundant transmission to the basic scheme, 4-4 model has the higher optimal probability of success delivery assuming the coded redundant-transmission scheme.

VI. Concluding Remarks

We consider multi-hop sensor networks where nodes are tandemly arranged and serially connected by unreliable lossy wireless links to deliver the sensor data to gateways at both

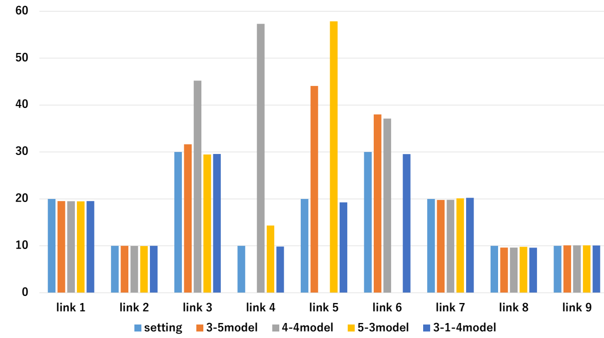


Fig. 5: Case1:Actual Loss Rate on Each Link

ends of the network. This restricted assumption is enough simple to deal with the problem analytically but, at the same time, is still of practical importance in real systems. Our contributions in this paper are as follows.

- The slot allocation is extended to heterogeneous links in terms of data transmission rate, by which our scheme covers more heterogeneous network configurations.
- The slot allocation is extended to new l-1-r type path model, by which our scheme covers all reasonable routing paths (assuming traditional half-duplex wireless links are used) and thus is applicable to network configurations in which any l-r type path model is not optimal.
- The synthetic simulation evaluations have validated the analytical optimization, shown the benefit of inter-packet XOR coding for FEC, and revealed the issues that are hard to consider in analytical models.

The research results have been achieved by the Resilient Edge Cloud Designed Network (19304), NICT, Japan.

References

[1] W. Li, J. Zhang, Y. Zhao,"Conflict graph embedding for wireless network optimization,"Proc. IEEE Infocom2017, 2017.
[2] Agussalim, M. Tsuru,"Message Transmission Scheduling on Tandem Multi-hop Lossy Wireless Links,"Proc. IFIP WWIC2016, pp.28–39, 2016.
[3] K. Jain, J.Padhye, V. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," Proc. ACM MobiCom '03, pp.66–80, 2003.
[4] I. Ho, "Packet Scheduling for Real-Time Surveillance in Multihop Wireless Sensor Networks With Lossy Channels," IEEE Trans. on Wireless Communications 14(2):1071–1079, 2015.
[5] Y. E. Sagduyu, and A. Ephremides, "Network coding in wireless queueing networks: Tandem network case,"Proc. IEEE Int. Symposium on Information Theory, pp.192–196, 2006.
[6] I. Rhee, A. Warrier, J. Min, and L. Xu,"DRAND: distributed randomized TDMA scheduling for wireless ad-hoc networks,"IEEE Transactions on Mobile Computing, 8(10):1384–1396, 2009.
[7] S. C. Ergen, and P. Varaiya,"TDMA scheduling algorithms for wireless sensor networks," Wireless Networks, 16(4):985–997, 2010.
[8] B. Zeng, and Y. Dong,"A collaboration-based distributed TDMA scheduling algorithm for data collection in wireless sensor networks," Journal of Networks 9(9):2319–2327, 2014.
[9] H. Tokito, M. Sasabe, G. Hasegawa, H. Nakano,"Load-Balanced and Interference-Aware Spanning Tree Construction Algorithm for TDMA-Based Wireless Mesh Networks,"IEICE Trans. Commun., E93B(1):99–110, 2010.
[10] P. Chaporkar, K. Kar, X. Luo, S. Sarkar,"Throughput and Fairness Guarantees Through Maximal Scheduling in Wireless Networks,"IEEE Trans. Information Theory 54(2):572–594, 2008.