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On the Performance of End-to-End Routing in Complex Networks with Intermittent Links

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***Abstract*—Emergence of IoT (Internet of Things) applications poses challenges on the networking infrastructure since those applications must accommodate a large number of end nodes (e.g., smart sensor devices), and the communication among those nodes are unreliable. In the last decade, DTN (Delay/Disruption-Tolerant Networking) has been actively studied by many researchers, which aims to provide efficient and reliable end-to-end communication in environments where end-to-end paths can not be reliably established. In DTN research, superiority and inferiority of several classes of routing mechanisms have been clarified. However, it is still an open question how effectively or ineffectively end-to-end routing performs in networks with *moderately* intermittent communication links. In this paper, we therefore address the following research questions: (1) does end-to-end routing perform effectively in a large-scale network with many nodes, each of which is connected with a few other nodes via intermittent communication links? (2) how is the average end-to-end message delivery delay affected by the degree (i.e., the total number of incoming and outgoing links) of source and destination nodes? To answer the above research questions, we analytically derive the average message delivery delay with end-to-end routing on a complex network with an arbitrary degree distribution.**

***Index Terms*—End-to-End Routing, Complex Network, Wireless Communication, Intermittently-Connected Links, Average Message Delivery Delay, Performance Analysis**

1. Introduction

Emergence of IoT (Internet of Things) applications poses challenges on the networking infrastructure since those applications must accommodate a large number of end nodes (e.g., smart sensor devices), and the communication among those nodes are unreliable [1]. IoT nodes are generally equipped with a short-range or long-range wireless communication such as ZigBee, 802.15.4, 802.11, LoRa, and SigFox [2]. Also, many IoT nodes are battery-powered so that those nodes frequently *sleep* to save the power consumption, which causes frequent disruption of the wireless communication since neither the transmission nor the reception is possible via the wireless communication always in the sleep mode. One of the challenges of those IoT applications is how to cope with a large number of nodes, each of which is connected with other nodes via an unreliable (e.g., intermittently-connected) communication link.

In the last decade, DTN (Delay/Disruption-Tolerant Networking) has been actively studied by many researchers [3]. DTN aims to provide efficient and reliable end-to-end communication in environments where end-to-end paths can not be reliably established because of several factors such as wireless communication uncertainty and dynamic changes in the network topology [4].

In DTN research, superiority and inferiority of several classes of routing mechanisms have been clarified [5]. Thus, it is well known that end-to-end routing is suitable for networks with non-intermittent (i.e., always connected) communication links. Also, it is well known that opportunistic routing is suitable for networks with highly intermittent communication links where any end-to-end path between source and destination nodes does not exist.

However, it is still an open question how effectively or ineffectively end-to-end routing performs in networks with *moderately* intermittent communication links. If the communication link is almost always connected (e.g., as in the Internet, Ethernet-based LAN, or 802.11-based LAN with little interference), end-to-end routing should be utilized. Similarly, if the communication is almost always disconnected (e.g., as in the planetary communication [6] or the deep-sea communication [7]), opportunistic routing should be.

In [8], we have derived the average end-to-end message delivery delay with either end-to-end routing or opportunistic routing (i.e., restrained epidemic routing). However, the major limitation of our comparative study [8] is its simplest analytic model. The network model in [8] is small-scale and homogeneous; i.e., the network is composed of the number N of nodes, each of which is mutually and equally connected with the identical intermittent communication link.

As IoT applications further prevail, the number of nodes in the network must be huge and at the magnitude of, for example, thousands, tens of thousands, or more. Understanding the potential as well as drawbacks of end-to-end routing in a large-scale (i.e., complex) network with intermittently connected links is crucial.

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In this paper, we therefore address the following research questions.

- Does end-to-end routing perform effectively in a large-scale network with many nodes, each of which is connected with a few other nodes via intermittent communication links?
- How is the average end-to-end message delivery delay affected by the degree (i.e., the total number of incoming and outgoing links) of source and destination nodes?

To answer the above research questions, we analytically derive the average message delivery delay with end-to-end routing on a complex network with an arbitrary degree distribution.

The organization of this paper is as follows. Section 2 describes the end-to-end routing discussed in this paper. Section 3 presents our analytic model. Section 4 derives the average message delivery delay. Several numerical examples are presented in Section 5, followed by discussions and answers to our research questions. Section 6 concludes this paper and discusses future works.

2. End-to-End Routing

End-to-end routing is a class of routing algorithms that tries to find available (i.e., operational) end-to-end paths between source and destination nodes (see Fig. 1). The rationale behind end-to-end routing is that, even when all communication links in the network are not reliable (i.e., intermittent), it is likely that several available end-to-end paths might exist. Generally, end-to-end routing is realized as a distributed algorithm in a sense that every node in the network autonomously constructs its routing table based on the information exchanged with neighbor nodes.

In this paper, as a typical end-to-end routing, we focus on a link-state end-to-end routing with periodic routing updates. In the end-to-end routing considered in this paper, every node periodically exchanges its link states with all neighbor nodes to know the current network topology so that an appropriate end-to-end path to an arbitrary destination node can be determined. Every source node refrains its message forwarding until at least a single end-to-end path becomes available.

Note that we do not assume a specific routing protocol such as RIP and OSPF intentionally since the main concern of this paper is to clarify the potential as well as the drawbacks of the class of end-to-end routing schemes on complex networks with intermittent communication links. Our analytic model presented in the following paper tries to capture the *essence* of several variations of end-to-end routing protocols, rather than the details of specific end-to-end routing protocols.

3. Analytic Model

Our analytic model consists of many nodes and intermittent links connecting those nodes (Fig. 2). The network topology is represented by undirected graph $G = (V, E)$. The number of nodes is denoted as $N \equiv |V|$, the degree of node v as d_v, and the degree distribution of graph G as $P(k)$. The average degree of graph G is denoted as $\overline{k}\,(\equiv \sum_k k\,P(k))$.

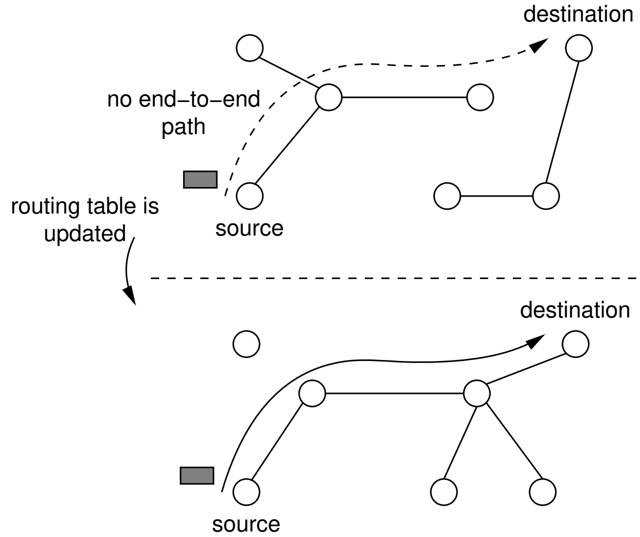

Figure 1. An example operation of message delivery with end-to-end routing

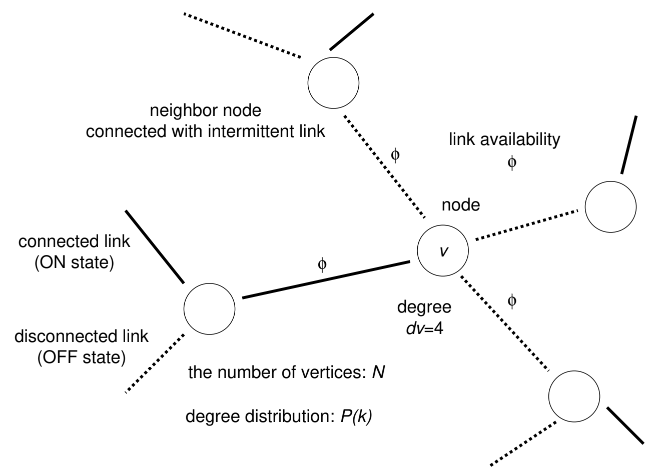

Figure 2. Analytic model

We focus on a message transfer from source node $s \in V$ to destination node $t \in V$ in the network.

It is assumed that the communication capacity of all links $e \in E$ is sufficiently large and that propagation delays of all links and queuing delays at intermediate nodes are negligibly small. In our analysis, link uncertainty is modeled by a two-state (i.e., ON and OFF states) continuous-time Markov chain [8] (Fig. 3). When link (u, v) is in the ON state, communication between node u and node v is

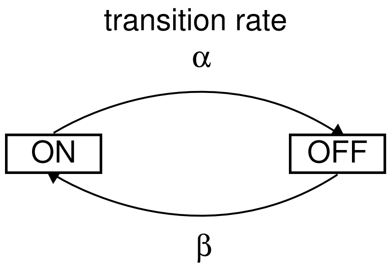

Figure 3. Two-state continuous-time Markov chain as link uncertainty model

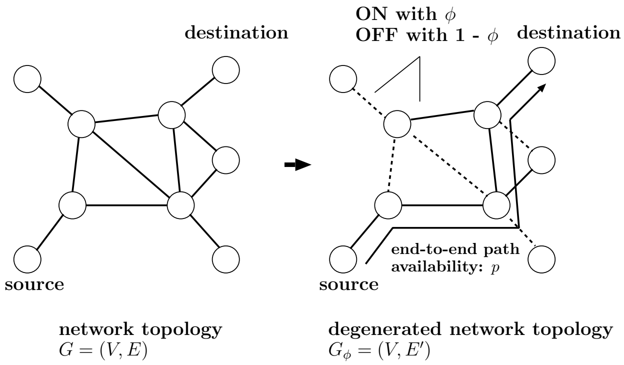

Figure 4. Message transfer with end-to-end routing in degenerated network

possible. On the contrary, when it is in the OFF state, communication between node u and node v is impossible. Transition rates from the ON state to the OFF state and from the OFF state to the ON state are denoted as α and β, respectively. Therefore, expected lengths of the ON state, $\tau_{\mathrm{O}N}$, and the OFF state, τ_{OFF}, are given by $1/\alpha$ and $1/\beta$, respectively.

4. Analysis

In end-to-end routing, we assume that every node periodically updates its routing table by exchanging information on link states with all neighbor nodes and it injects the message into the network only when an end-to-end path is available (Fig. 4). We assume that the update intervals of rounting tables at nodes are identical. The update interval is denoted by Δ. Note that the update interval icludes the convergence time of the routing protocol.

We introduce *end-to-end path availability p*, which is the probability that the source node observes at least a single end-to-end path to the destination node through an arbitrary number (including none) of intermediate nodes. The average message delivery delay D is given by

$$D = \sum_{n=1}^{\infty} (1-p)^{n-1}\, p\,(n-1)\,\Delta. \tag{1}$$

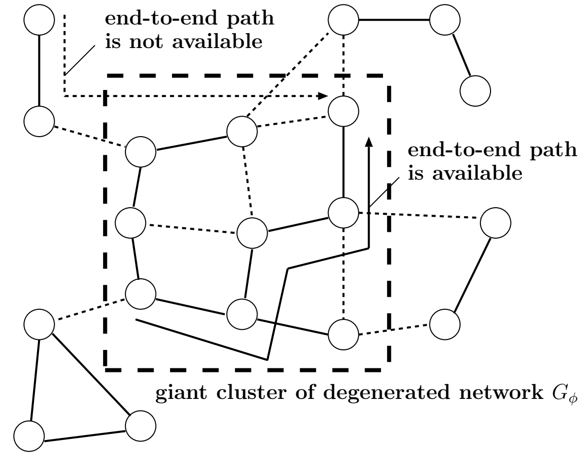

Figure 5. Example of degenerated network G_ϕ

The link availability is denoted by ϕ.

$$\phi = \frac{\tau_{\mathrm{O}N}}{\tau_{\mathrm{O}N} + \tau_{OFF}} \tag{2}$$

End-to-end path availability p is the probability that at least a single path is available between source node s and destination node t. Let G_ϕ be a subgraph of graph G (degenerated network), composed of available links in their ON states at a given point. Probability p that at least a single path is available between source node s and destination node t can be approximated by the probability that both source node s and destination node t belong to the giant cluster on graph G_ϕ (Fig. 5).

$$p \simeq (1 - u_{d_s})(1 - u_{d_t}) \tag{3}$$

In the above equation, u_k is the probability that a node of degree k *does not* belong to the giant cluster.

Let u be the probability that a node in graph G_ϕ is not connected to the giant cluster via a specific neighbor node. Since u_k is the probability that all k links of a node of degree k are not connected to the giant cluster, we have [9]

$$u_k = u^k. \tag{4}$$

Let $P_\phi(k)$ denote the degree distribution of graph G_ϕ. Nodes of degree k in graph G will have degree k in graph G_ϕ with probability ${}_kC_k(1-\phi)^k$. Similarly, those will have degree $k-1$ with probability ${}_{k+1}C_k(1-\phi)^{k-1}\,\phi$.

Thus, $P_\phi(k)$ is given by

$$\begin{aligned} P_\phi(k) &= {}_kC_k(1-\phi)^k P(k) \\ &\quad + {}_{k+1}C_k(1-\phi)^k \phi P(k+1) \\ &\quad + {}_{k+2}C_k(1-\phi)^k \phi^2 P(k+2) \\ &\quad + \ldots \\ &= \sum_{n=0}^{\infty} {}_{k+n}C_k(1-\phi)^k \phi^n P(k+n). \end{aligned} \tag{5}$$

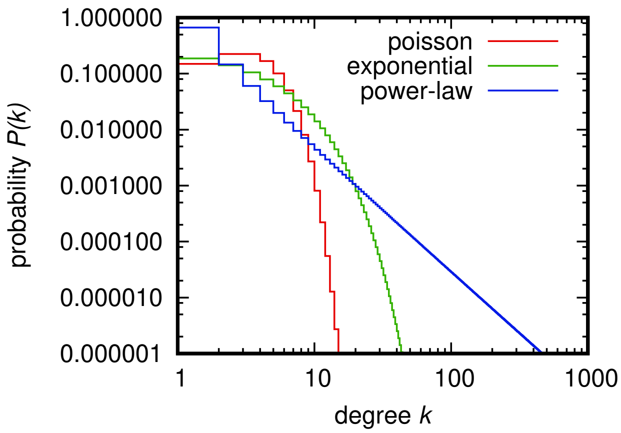

Figure 6. Degree distributions (Poisson distribution, exponential distribution, power-law distribution) for $\overline{k} = 3$

The excess degree distribution [9] of G_ϕ, which is the degree distribution of nodes reached by following a link, is given by

$$Q_\phi(k) = \frac{(k+1)\, P_\phi(k+1)}{\phi\, \overline{k}}. \quad (6)$$

Furthermore, u is equal to the probability that none of the links of a neighbor node, which is reached by following a link from a node in graph G_ϕ, are connected to the giant cluster. Thus, probability u satisfies

$$u = \sum_{k=0}^{\infty} Q_\phi(k)\, u^k. \quad (7)$$

Solving Eq. (7) yields probability u.

5. Numerical Examples

In what follows, through several numerical examples, we investigate how effectively or ineffectively end-to-end routing performs in complex networks with moderately-intermittent communication links.

As typical complex network models, we use three types of degree distributions for an original network topology — Poisson, exponential, and power-law, each of which has essentially different properties (Fig. 6). Poisson and exponential distributions are *short-tail* distributions whereas the power-law distribution is a *long-tail* (scale-free) distribution. The Poisson distribution is a good approximation of the Binomial distribution when the number N of nodes is large.

The average degree $\overline{k}$ (i.e., density) of the original network and the link availability ϕ are varied to examine the characteristics of end-to-end routing in diverse environments.

Note that the average message delivery delay derived as Eq.(1) is solely depended on the link availability ϕ, which is determined by the *ratio* of the expected ON length (τ_{ON}) to the total of expected ON and OFF lengths ($\tau_{ON} + \tau_{OFF}$). Thus, in our numerical examples, the link availability ϕ is varied. Unless stated otherwise, we use the following settings; the degree distribution of the network topology is the Poisson distribution, the update interval Δ of the routing table is 10 [s], the degree d_s of the source node is $\overline{k}$, and the degree d_t of the destination node is $\overline{k}$.

We first examine how well or how badly the end-to-end routing performs on complex networks with diverse densities. Figure 7 illustrates the relationship between the link availability ϕ and the average message delivery delay D for different densities (i.e., different average degrees $\overline{k}$). Note that results for $\overline{k} \geq 3$ are almost indistinguishable from the x-axis. This figure clearly indicates that the end-to-end routing performs quite effectively when the network is not sparse as like $\overline{k} = 1$. It should be noted that the end-to-end routing could be acceptable even when the network is sparse (e.g., $\overline{k} = 1$) and the link availability is not high (e.g., $\phi = 0.6$). In such a case, the average message delivery delay is around 40 [s], which might be usable for non-real time applications such as environment monitoring and infrequent control message exchanges.

However, the effectiveness of the end-to-end routing highly depends on the degree of source and destination nodes. In other words, the performance of the end-to-end routing depends on how tightly source and destination nodes are connected with their neighbor nodes. Figure 8 depicts how the average message delivery delay is affected by degrees of source and destination nodes. In this figure, the degree of the source node, d_s, is changed from $\overline{k}\,(=3)$ to 1. The degree of the destination node is changed from 1 to 5. This figure indicates that the message delivery from *loosely-connected* node to *loosely-connected* node takes a longer time. This is because *tightly-connected* nodes (e.g., hub nodes) are likely to have an end-to-end path to their peer nodes. Such finding implies that the applicability of the end-to-end routing must be determined based not only on the density of the network but also on the degree distribution of the network.

We should note that the above observation is only valid for sparse networks, as shown in Fig. 9. Again, this figure shows the relation between the link availability ϕ and the average message delivery delay D. In this figure, the density $\overline{k}$ of the network is 5, rather than 3 as in Fig. 8. This figure indicates that when the network is not sparse, the degrees of source and destination nodes do not have a significant impact on the average message delivery delay.

Finally, we investigate how the type of degree distribution affects the performance of the end-to-end routing. Figure 10 illustrates the average message delivery delay under different types of networks, each of which has either the Poisson, the exponential, or the power-law distribution. Note that all results for $\overline{k} = 5$ are almost indistinguishable from the x-axis. This figure indicates that the effectiveness of end-to-end routing is highly dependent on the type of degree distribution. Namely, even when the network density is the same (i.e., $\overline{k} = 3$), the different degree distribution results in significant differences in the average message delivery delay.

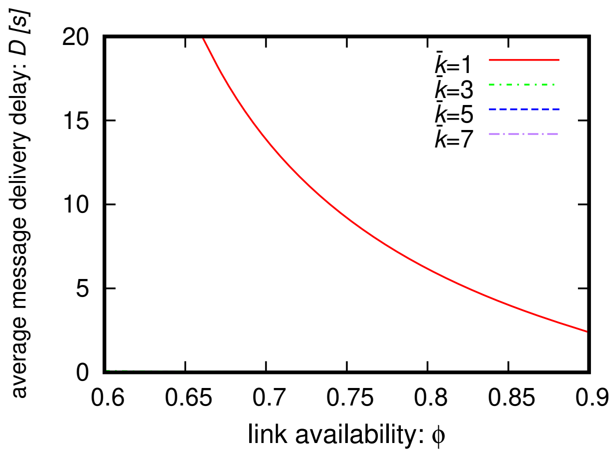

Figure 7. Relationship between the link availability ϕ and the average message delivery delay D for different densities

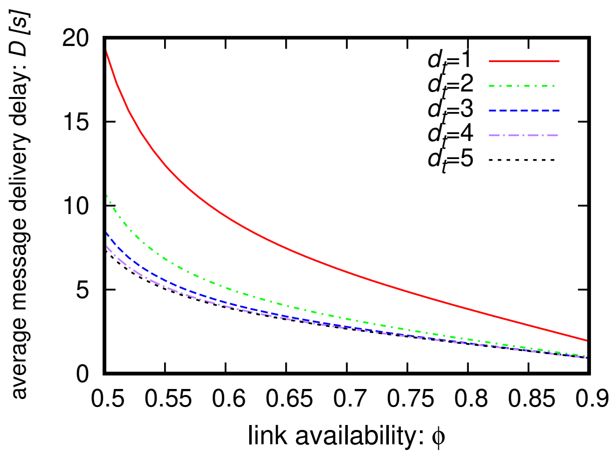

Figure 8. Relationship between the average message delivery delay D and degrees of source and destination nodes

Moreover, somewhat surprisingly, the end-to-end routing achieves the best performance when the degree distribution is *exponential*. This implies that, for connectivity-wise, long-tail degree distributions of the network topology have favorable properties such as the robustness to node/link failures and the short diameter. However, for performance-wise, long-tail degree distributions could be harmful.

6. Conclusion

In this paper, we have investigated how effectively end-to-end routing performs in complex networks with moderately-intermittent communication links. Specifically, we have analytically derived the average message delivery delay with the end-to-end routing on a complex network with an arbitrary degree distribution. Through several numerical examples, we have shown that the end-to-end routing performs quite effectively when the network is not sparse

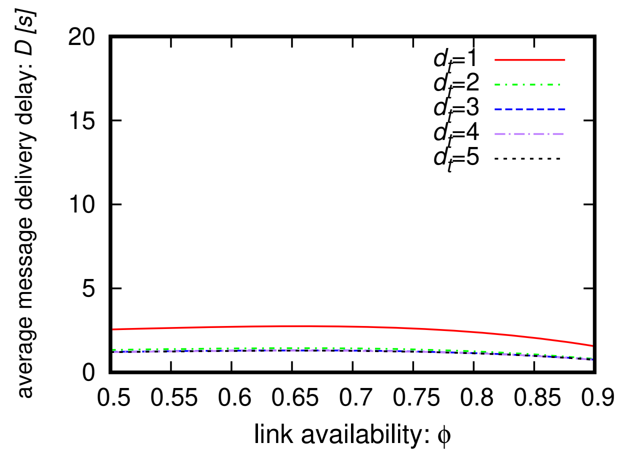

Figure 9. Relationship between the average message delivery delay D and degrees of source and destination nodes

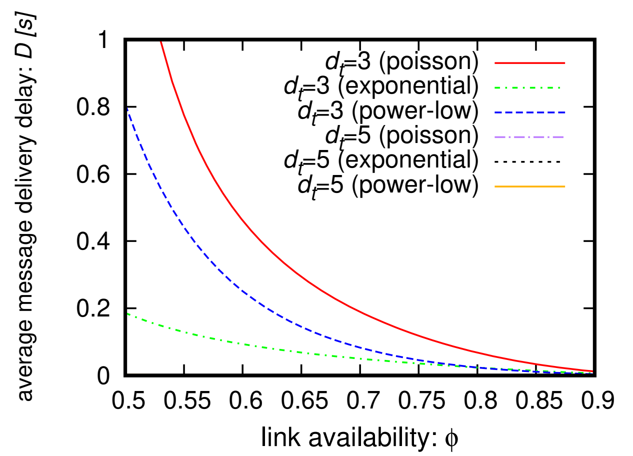

Figure 10. Relationship between the average message delivery delay D and degree distribution

and that the effectiveness of the end-to-end routing highly depends on the degrees of source and destination nodes.

Our future work includes the extension of our analysis to take account of the details of major routing protocols such as OSPF and BGP. Also, the design of an end-to-end routing protocol for complex networks is of great value.

Acknowledgments

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