Unreliable Multi-hop Networks Routing Protocol For Age of Information-Sensitive Communication

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***Abstract*—It is an important problem to study multi-hop communication networks with unreliable links and various nodes forwarding costs, where the freshness of the messages is significant. On unreliable networks, existing time-sensitive utility-based routing protocols provide efficient routing based on a simple utility model that is linear with time. In this work, we introduce an Age of Information (AoI)-sensitive utility model for unreliable networks, in which each periodically generated message has an attached time-sensitive total utility that decays over time following the AoI model. This model provides a good balance between cost and delay. We propose an optimal routing algorithm that guarantees the total expected utility of the messages would be maximized. Our algorithm maximizes expected utilities by forwarding the messages via nodes along the optimal path whenever the beneficial reward will cover the expected total decrease in utility, and dropping them whenever it would not. Finally, we conduct a simulation to evaluate the effectiveness of our algorithm.**

***Index Terms*—Age of information (AoI), multi-hop networks, unreliable networks, utility-based routing.**

I. INTRODUCTION

In multi-hop communication networks, it is important to study the problem of having unreliable links with different reliability values where the nodes would incur different forwarding cost values. Moreover, the timeliness of the delivered messages is also important in many applications [1]. For unreliable networks, we present an Age of Information (AoI)-sensitive utility model, where each periodically generated message has an associated time-sensitive total utility that decays over time following the AoI paradigm [2]. This model provides a good balance between cost and delay. We then propose an optimal routing algorithm that guarantees to maximize the total expected utility of the messages. We utilize the AoI because it is a measure of the freshness of information.

In our work, we consider a multi-hop network that has unreliable links where each node has a certain forwarding cost. The messages are generated periodically at the source. The unreliability of the links causes the messages to arrive in a stochastic way. As link failure is intermittent, repeated transmissions are allowed with additional forwarding cost. The time taken by a link in case of failure is probabilistic following the exponential distribution. Our objective is to design an optimal routing algorithm that guarantees to maximize the total expected utility of AoI messages. We assume that there are no simultaneous message transmissions in the network, i.e., there are no extra processing and queueing delay.

II. PROPOSED MODEL

We create a utility function that reflects the freshness of messages. We assign each message a beneficial reward value b that reflects the significance of the message. We model the total utility function to decrease as the messages become less fresh following the AoI paradigm. This means each message could have a different intrinsic value alongside the importance of the freshness of this message. However, in the more typical case where each message (e.g. status update) does not have an intrinsic value, the model would apply by fixing the value of b for all the messages. This model is a generic model that includes forwarding cost for the nodes and beneficial reward of the messages. As in previous work, we aim to maximize the expected utility, which is equal to the benefit minus the expected cost [3, 4]. The message utility depends not only on their beneficial reward values and the total cost of going through the nodes of the selected path, but also on both the link reliability values of that selected path and the freshness of the message. Therefore, we design the expected utility function which integrates the beneficial reward, nodes cost, and message freshness of the remaining path in order to find an optimal routing scheme in unreliable networks. A practical example of the model would be the weather conditions update where we gain a specific reward that would decrease as the update becomes less fresh.

In our model, messages will be generated periodically in a deterministic way. The time period between two messages generated at the source node is T. Each message carries an intrinsic beneficial reward b, which is the reward gain in case of the arrival of the message from the source node s to the destination node d. We will represent the total cost charged on the message utility by the network nodes using C. The total utility of the message is linearly proportional with the age of the message. (i.e. the message freshness). This means that higher AoI values of the message ($\Delta(t)$) make the total utility decrease. To generalize, we set a factor of δ to represent the proportion by which the AoI affects the total utility with respect to the total forwarding cost C. This factor of δ is set depending on the importance of the age of the message, with respect to b and the total cost of forwarding C. If the total expected utility goes below $-C$, discarding the message with that cost would be more beneficial. Hence, we end up with a time-sensitive AoI-based utility model of messages $u(t)$ shown in Equation 1. Figure 1 shows the utility evolution.

$$u(t) = max\{-C, b - \delta\Delta(t) - C\} \tag{1}$$

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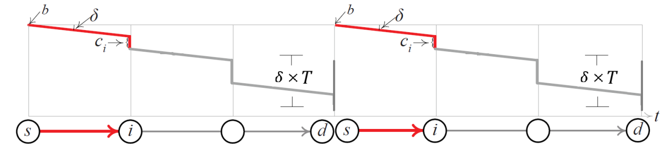

Fig. 1: An illustration showing the change of the utility function over the transmission for two consecutive messages.

We consider that the probability that a message transmits successfully in the link between nodes i and j is denoted by $p_{i,j}$. In case the link between nodes i and j succeeds in transmitting the message, the message would take $\tau_{i,j}$ time units. However, in case the link between nodes i and j fails to transmit the message, the failure happens after some time that follows the truncated exponential distribution with parameter $\lambda_{i,j}$, where $\lambda_{i,j}$ is the expected value of the natural exponential distribution that can be characterized in terms of $\tau_{i,j}$ and $p_{i,j}$. In case of failure, the node may try the same link immediately while having the same previous success chance. In addition, we consider a forwarding cost at each node i to be denoted by c_i. This forwarding cost would be incurred each time the node tries to forward the message regardless of whether the message was successfully or unsuccessfully delivered.

III. THE OPTIMAL SOLUTION OF THE PROBLEM

We provide a centralized optimal solution for the problem. First, the optimal solution is the solution that chooses the path which guarantees that the expected value of the utility $\mathbb{E}[u(t)]$ is maximized, where the notation $\mathbb{E}[.]$ represents the expected value. In other words, the solution is based on choosing the path that minimizes the expected total reduction of the AoI-based utility $(\delta\Delta(t) + C)$. Since the links of the network are intermittently unreliable and would succeed only at a certain probability, the optimal solution will be based on the expected total reduction of the utility given that the links are used repeatedly until success in delivering the message. That is done with the consideration of the exponential probability distribution for the time taken in case of failure. The expected reduction of utility from node i to j can be evaluated by adding the reduction of utility in case of success $R^s_{i,j}$ with the expected reduction in case of failure $R^f_{i,j}$ times the expected number of failures before the first success.

$$\mathbb{E}[R_{i,j}] = R^s_{i,j} + (\frac{1}{p_{i,j}} - 1)R^f_{i,j} = \frac{(1 - p_{i,j})}{(-p_{i,j})\log p_{i,j}}\delta\tau_{i,j} + \frac{c_i}{p_{i,j}} \tag{2}$$

Algorithm 1 returns the path with minimum expected total utility reduction utility in a way similar to the Bellman-Ford algorithm. We call this path the "optimal path". $\mathbb{E}[D_k[i]]$ is the expected "distance" from the source node s to node i when we allow at most k links. This distance is the total utility reduction for the path taken from s to i. $\pi[i]$ is the predecessor node of i in the optimal path. We represent the sudden utility increase once the message is received by assigning a cost of $(-\delta T)$ at d. The routing protocol utilizes the optimal path produced by Algorithm 1 by trying to forward the message to the next node on the path or discarding it depending on whether the total expected decrease of utility is larger than the expected utility. The optimal protocol sticks with the optimal path produced by Algorithm 1 regardless to the number of failures at the links.

Algorithm 1 Determining the Optimal Path.

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Require: $\delta, T, V, E$. //i.e. nodes and links sets $V$ and $E$.
Ensure: Minimum cost $(C + \delta\Delta(t))$ from $s$ to $d$.
Initialization: $\forall i \in V, \mathbb{E}[D_k[i]] = \infty \ \forall k, \pi(i) = \text{NIL} \ \forall i \in V$.
$c_d = -\delta T$.
$\mathbb{E}[D_k[s]] = 0 \ \ \forall k$.
for $k$ from $1 \rightarrow (|V| - 1)$ do
    for $(i, j) \in E$ do
        Evaluate $\mathbb{E}[R_{i,j}]$ from Equation 2.
        if $\mathbb{E}[D_{k-1}[i]] + \mathbb{E}[R_{i,j}] < \mathbb{E}[D_{k-1}[j]]$ then
            $\mathbb{E}[D_k[j]] = \mathbb{E}[D_{k-1}[i]] + \mathbb{E}[R_{i,j}]$.
            $\pi[j] = i$.
        else $\mathbb{E}[D_k[j]] = \mathbb{E}[D_{k-1}[j]]$.
return the optimal path $\pi[d], \pi[\pi[d]], \ldots$
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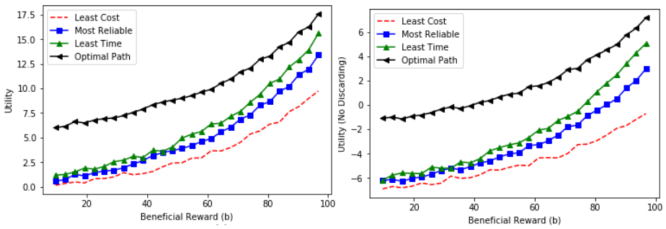

Fig. 2: A sample of the simulation results from running the different algorithms when $\delta = 1$. The left figure is when we enable discarding. In the right figure, the algorithms are forced to deliver without discarding so that large negative utility values would occur.

IV. SIMULATION

We compare our optimal algorithm with the algorithm that chooses the route with the least forwarding cost, the algorithm that chooses the route with the highest total reliability, and the algorithm that chooses the path with the least total links' expected delay time. The generation of messages at the source node is periodic. Figure 2 shows a sample of the simulations done. The topology is randomly-generated with delay values and failure probabilities distributed normally throughout the network. The parameters are distributed as follows: $p_{i,j} \sim N(p_{\text{mean}}, \sigma^2), p_{\text{mean}} = 0.5, \sigma = 0.2 \quad \forall (i,j) \in E.c_i \sim N(c_{\text{mean}}, \sigma^2), \sigma = 1, c_{\text{mean}} = 4, \quad \forall i \in V$.

Our future work will include more in-depth analysis and simulation. We will consider the stochastic generation of messages at the source node. In addition, we will study the case of multiple messages sent at the same time, where the network would allow the redundancy of the same message.

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