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A Limiter on Dynamic Metrics to Reduce Routing Loops in Wireless Mesh Networks

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Abstract: To improve the communication performance in IEEE802.11-based wireless mesh networks (WMNs), several dynamic metrics have been proposed. However, all of them have a severe risk of generating temporary routing loops which may cause severe congestion and disruption of communications. Although the routing loop is an essential problem that degrades network performance, no essential solution is provided so far for wireless multihop networks. In this paper, we propose a mechanism called Loop-free Metric Range (LMR) to make existing dynamic metrics loop-free by restricting the range of metric values to change. LMR is applicable to a major part of existing metrics including ETX, ETT, MIC, etc. without any message overhead. We first provide theoretical results that shows LMR guarantees loop-freedom if no message loss takes place. We next show that LMR is also practically effective in practical scenarios where message loss may take place; we show through simulation and actual evaluations that LMR works effectively as a limiter on dynamic metrics to reduce routing loops and to improve network performance through similation and real evaluation.

Keywords: wireless mesh networks, routing metrics, routing loops

1. Introduction

Wireless Mesh Networks (WMNs) [1] have been studied as a promising next generation wireless infrastructure to provide reliable broadband communication services in a wider area. However, although tremendous efforts have been dedicated to improving performance, WMNs have not been achieved a performance on a practical level due to severe congestion and interference.

As one of the important techniques to improve the network performance, dynamic link metric is counted. Dynamic metric is a value computed in real time that represents a quality of a link. Being incorporated into shortest-path computation, routing protocols are enabled to compute better paths that reflects on up-to-date link qualities.

In the literature, many proposals [3], [4], [5], [6], [7], [8], [9], [10] have appeared and they significantly improved communication throughput in WMNs. However, dynamic metrics inevitably suffer from temporary routing loops which may cause disruption of connections. As for how harmful the loops are, Speakman et al. [16] reported that the loops cause severe congestion, and they proposed a technique to detect and suppress (drop) looping packets, which brought about a 20% improvement of packet delivery ratio in mobility scenario. This proposal may reduce the performance degradation coming from packet looping, but it is not a complete solution. Since looping prevents flows from reaching the destinations, users may experience short-time but not negligible disruption of communication when their flows are caught in loops. To build up WMNs as a reliable wireless infrastructure, such service disruption is not allowable. The elimination of temporary loop formation is therefore an important task for future WMNs.

From the motivation above, we have proposed a new loop-free dynamic metric which we call Loop-free Link Duration (LLD) [8], which decreases link metrics gradually within the "safe range" (i.e., within the range of loop-free) as long as the links continue to be stable. Using periodical synchronization messages, LLD guarantees loop-freeness under the condition that no node or link failure occurs. LLD is actually the first loop-aware dynamic metrics ever, but LLD has a drawback in practice that it cannot treat congestion which requires raising metrics because LLD monotonically decreases metrics. More capable loop-free mechanisms are desired.

In this paper, we propose a new mechanism called Loop-free Metric Range (LMR) to reduce temporary routing loops for shortest-path based proactive link-state routing protocols such as OLSR [2] in WMNs. We discovered that the possibility of temporary loop formation depends on the dynamics of metrics measured by the ratio of metric value changes per unit time, and therefore limiting the range of metric transition per unit time can eliminate routing loops theoretically. Since LMR is based on this simple strategy, LMR is applicable to many existing dynamic metric proposals as an extension in order to append a loop-free property without any additional message overhead. We provide theoretical results on LMR, as well as traffic evaluation results that show the practical effectiveness of LMR to reduce routing loops and improve communication performance.

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This paper is organized as follows. In Section 2, we present related work on dynamic metrics and loop-free mechanisms to clarify the contribution of this work. In Section 3, we describe the proposed mechanisms LMR and in Section 4 we give the theoretical results on LMR. We present simulation results on creating loops in Section 5, and evaluation results on real environment in Section 6. Finally in Section 7, we conclude the work.

2. Related Work

Much work on dynamic metrics and loop-free routing in the literature is related to this work. Here we show several essential results among them to clarify the contribution.

We first show the results on dynamic metrics in WMNs. Several proposals contribute to improve throughput of WMNs as follows: Couto, et al. proposed ETX (Expected Transmission Count) [3] link metric, which is defined as the expected number of transmissions required to deliver a packet. ETX is computed from the ratio of success transmissions which is measured by sending periodical probe packets on a link. ETX metric is the first proposal which succeeded in improving traffic throughput in MANETs against instability of wireless communications. Later, Draves et al. presented ETT (Expected Transmission Time) [4] which extends ETX by taking link speed into consideration as $\mathrm{ETT} = \mathrm{ETX}\frac{S}{B}$, where S is the packet size and B is the link bandwidth. WCETT was also proposed in this paper [4], which takes bottleneck channel affection into account to compute path metrics under multi-channel environments. WCETT is computed as $\mathrm{WCETT} = (1-\beta)\sum_{i=1}^{n}\mathrm{ETT}_i + \beta \max_{1\le j\le k} X_j$, where n is the number of hops on a routing path, k is the number of available channels for multiradio operation, and $X_i = \sum_{\text{Hop } i \text{ on channel } j}\mathrm{ETT}_i$. Note that $\beta\max_{1\le j\le k} X_j$ represents the bottleneck channel affection.

Note that WCETT is not link metrics but path metrics. ("Link metrics" here means the *additive metric* where a path metric is computed as the summation of all the link metrics included in the path.) Yang et al. [6] pointed out that path metrics such as WCETT may create loops even under static metric situation, and that the necessary and sufficient condition for path metrics to be statically loop-free is to satisfy the property called *isotonicity* introduced in the work of Sobrinho [11]. Yang et al. also proposed a new path metric called MIC (Metric of Interference and Channel-switching) [6], which metric values can be decomposed to the isotonic metrics on a virtual network. This means that MIC is statically loop-free and is computed efficiently using the general shortest-path finding algorithms.

As an additive metric, Murthy et al. presented LDAR [7], which is computed based on precise measurements of experienced delay in a node and their statistics as follows: $d_i = d_i^{\text{process}} + d_i^{\text{queue}} + d_i^{\text{transmit}}$ where d_i^{process} is the processing delay in node i, d_i^{queue} is the queuing delay, d_i^{transmit} is the transmission delay of the 802.11 MAC protocol, and they all are computed based on experienced measurements.

Among the past proposals on dynamic metrics [3], [4], [5], [6], [7], [8], [9], [10], there is no proposal which cares temporary loops except for LLD [8] described afterwards. The contribution of our work is to present a mechanism to add loop-free property to the existing additive metrics such as ETX, ETT and LDAR.

As for loop-free routing, there are several results in wired network routing protocols. The first loop-free routing scheme was presented as DUAL [12], which controls the sequence of routing tables to update when the topology (or metrics) changes in distance-vector routing schemes. Later, Francois et al. [13] presented a loop-free link-state routing scheme from a similar strategy. They are always loop-free, however, since they require control messages for each topology change, the overhead is not sufficiently low for MANET.

As another side, there are the studies on the safe (i.e., loop-free) range of metric modification [14], [15]. They analyzed the case of changing one metric value simultaneously, and give an algorithm to compute the safe range of the value to be modified. They clarified an important property of routing loops, but it is not practical since they require a kind of central control so as not to allow changes of more than two metric values simultaneously.

As the method to treat metrics of multiple links, LLD (Loop-free Link Duration) [8] metric appeared for ad-hoc networks. LLD is the first distributed loop-free dynamic metrics based on the concept of "safe range." The LLD metric of link l is monotonically decreased as $\delta^t(l) = ab^t + c$ where t is the time past since l is generated, b is the parameter $0 < b < 1$ to control deceleration speed, a and c is the parameter to determine the initial value and the final (converging) value of the metric. LLD guarantees loop-freedom in case of no addition/deletion of links using additional sync messages. However, LLD has a critical fault when applied to WMNs that LLD cannot raise the metric value. Specifically, if we want to raise the metric, we have to reset it to the initial LLD value, which would generate loops with high probability. In fact, LLD metric is designed to measure the 'stability' of links such that long-living links with no disruption get low values, in order to select stable links as the communication paths. For this purpose, the monotonically decreasing metric works well. In contrast, in WMNs, the 'quality' of links, which changes up and down with time, should be the main criteria to select the optimal communication paths. In practice, since various dynamic metrics that represent link quality have been proposed, one desirable contribution is to add a loop-free property to them to make the most of the advantages of the past research work.

In the context above, LMR is the first loop-free mechanism for wireless environments which treats both the increase and decrease of metrics. The approach based on "safe range" is suitable for wireless environments due to low additional overhead. Furthermore, our method LMR is applicable to any additive dynamic metric proposed so far that works over link-state routing, and adds the loop-free property to them to stabilize the network traffic.

3. A New Loop-free Mechanism LMR

Our Loop-free Mechanisms LMR is based on the discovery that the possibility of creating loops depend on the difference ratio of two successive metric values for a link. Therefore, our approach for loop-freeness is extremely simple in that it limits the range of metric values to change based on the ratio from the current metric value. More specifically, if we let $m_{l,t}$ be the metric of link l at time t, then, the metric of l at time t should hold

$$m_{l,t-t'} r^{-t'} \le m_{l,t} \le m_{l,t-t'} r^{t'}, \tag{1}$$

where $r > 1$ is what we call loop-free metric stretch. Here, loop-free threshold of r is determined depending on two factors: the diameter of the network in hop count, and the range of the metric values to take. (Namely, every metric value should always be in this range. To refer to this metric range, we define the lower and upper bound of the range by $m_{\min}$ and $m_{\max}$, respectively.) In the next section we show that this simple condition can eliminate routing loops.

Our mechanism works in proactive link-state routing protocols for WMNs such as OLSR. Generally in this kind of routing scheme, each node periodically sends link information messages which include the information of the links connected to the node. The link information is then propagated hop by hop and finally every node comes to know the entire topology of the network. If some dynamic metrics are deployed in the network, each node advertises the latest metric values in each of the periodical messages. The main reason for routing loop creation is the propagation delay occurring in this situation, i.e., some routing tables are computed with old metric values as a result.

In LMR, by limiting the range of metric change, reduce the difference between old and new metric values used simultaneously in a network. Consider that each node computes the new metric value when it sends a new link information message. Here, all that the LMR node needs to do is to advertise the metric value closest to the new metric value computed by the deployed dynamic metric module, from the safe range of Eq. (1). Note that Eq. (1) fits to this situation when we regard t' as the interval of periodical message, t as the current time, and $r^{t'}$ as the threshold of the ratio between successive two metric values of a link.

4. Analysis for Loop-free Metric Range

4.1 The Case of One-time Metric Change

In this section, we give an analysis on the safe (i.e., loop-free) range of metric values starting with the simple case. Let $G = \{V, E\}$ be a network, where V is a set of nodes and E is a set of directed links. For a pair of nodes $n_1, n_2 \in V$, we call them *adjacent* if $(n_1, n_2) \in E$. A sequence of nodes $p = (n_1, n_2, \dots, n_m)$ where $(n_k, n_{k+1}) \in E, k = 1, 2, \dots, m-1$ is called a *path*. A path $p = (n_1, n_2, \dots, n_m)$ where $n_1 = n_m$ is called a *cycle*. The *metric* of link l at time t is denoted by $m_{l,t}$. The *metric* of path p at time t is denoted by $\delta^t(p) = \sum_{l \in p} m_{l,t}$. Let $D_t(d) = (V, E_t)$ be a directed acyclic graph (DAG) representing the set of the shortest paths destined to d under the metric $m_{l,t}$. (If we consider equal-cost paths, the shortest paths form DAG rather than a tree.)

We first discuss loop-freedom in the simple case; consider the case where every node knows that the metric of each link $l \in E$ is $m_{l,0}$ at time 0, and every node updates metrics of its links only once at time t' simultaneously. In this case, it is clear that finally every node comes to know the same link metric $m_{l,t'}$ for every link l and the paths converge, but during the time period of propagating new metrics, two metrics (i.e., the old and the new one) are mixed in the network and this may cause temporary loops.

In our analysis, we first assume an arbitrary cycle C in the network G, and consider the condition on r under which the cycle

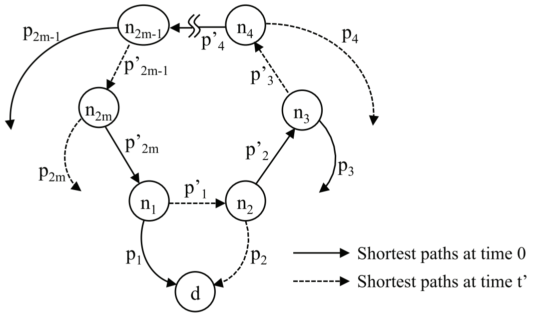

Fig. 1 The general case of routing loops.

C is never created at any time. By obtaining the condition on r which eliminates any cycle in the network, we can guarantee that no loop is created in the network.

Now we give a specific definition of the assumed loop situation to obtain a loop-free condition. **Figure 1** shows the general situation of a routing loop created by paths destined for d, which supposes an arbitrary cycle C in G. To have C created, 'old' and 'new' shortest paths (i.e., those at time 0 and time t', respectively) must appear by turns in C. In other words, there must be a sequence of nodes $n_1, n_2, \dots, n_{2m}$ in C that change their shortest paths. Specifically, for nodes with odd indices, i.e., $n_{2k-1} (1 \le k \le m)$, we let p_{2k-1} be the old shortest path from n_{2k-1} to d that does not include n_{2k}, which is the next node in C in the node sequence. Then, the new shortest paths from n_{2k-1} must include n_{2k}. So, we let $p'_{2k-1} + p_{2k}$, the concatenation of two shortest paths, be the shortest path at time t', where p'_{2k-1} be the shortest path from n_{2k-1} to n_{2k}, and p_{2k} be the shortest path from n_{2k} to d at time t'. Similarly, as for nodes with even indices $n_{2k} (1 \le k \le m)$, the old shortest paths must include the next node n_{2k+1}. (Please assume $n_{2m+1} = n_1$.) Therefore, we let $p'_{2k} + p_{2k+1}$ be the old shortest path from n_{2k} to d, where p'_{2k} is the shortest path from n_{2k} to n_{2k+1} at time 0.

Note that we focus on the smallest value of r to form C. The worst case is that all links in p_{2k-1} and p'_{2k} (the solid arrows in Fig. 1) increase their metrics as much as possible, while all links in p_{2k} and p'_{2k-1} (the dotted arrows in Fig. 1) decrease their metrics as well. Consequently, we may let the former paths be the shortest paths at time 0, and let the latter paths be those at time t'. Here, the next statements stand:

Proposition 1 A sufficient condition which guarantees the cycle never created is that $D = D_0(d) \cup D_{t'}(d) = (V, E_0 \cup E_{t'})$ does not include C.

Theorem 1 Assume that $m_{l,0} r^{-t'} \le m_{l,t'} \le m_{l,0} r^{t'}$ for every link $l \in E$. Then, the sufficient condition of r that $D = D_0(d) \cup D_{t'}(d) = (V, E_0 \cup E_{t'})$ does not include C is the following:

$$r \le K^{\frac{1}{2t'}}$$

where

$$K = \frac{\sum_{k=1}^{m} (\delta^0(p_{2k-1}) + \delta^0(p_{2k}) + 2\delta^0(p'_{2k-1}) + 2\delta^0(p'_{2k}))}{\sum_{k=1}^{m} (\delta^0(p_{2k-1}) + \delta^0(p_{2k}))}$$

Proof: As mentioned above, the worst case that cycle C is the most likely to be included in D is when $m_{l,t'} = m_{l,0} r^{t'}$ for every link $l \in p_{2k-1} \cup p'_{2k} (0 < k \le m)$ and $m_{l,t'} = m_{l,0} r^{-t'}$ for every link $l \in p_{2k} \cup p'_{2k-1} (0 < k \le m)$. Conversely, if C is not included in D

in this worst case, C is never included in D. In the following we only consider this worst case.

By comparing the length of old and new shortest paths from node n_{2k-1} to d at time 0 and t', the following two formulas stand:

$$\delta^0(p'_{2k-1}) + \delta^0(p_{2k}) \geq \delta^0(p_{2k-1}), \quad (2)$$

$$r^{t'}\delta^0(p_{2k-1}) \geq r^{-t'}\delta^0(p'_{2k-1}) + r^{-t'}\delta^0(p_{2k}). \quad (3)$$

Similarly, by comparing the old and new shortest paths from node n_{2k} at time 0 and t', the following two formulas stand:

$$\delta^0(p_{2k}) \geq \delta^0(p_{2k+1}) + \delta^0(p'_{2k}), \quad (4)$$

$$r^{t'}\delta^0(p_{2k+1}) + r^{t'}\delta^0(p'_{2k}) \geq r^{-t'}\delta^0(p_{2k}). \quad (5)$$

Equation (3) can be transformed as follows:

$$\delta^0(p_{2k+1}) \geq r^{-2t'}\delta^0(p'_{2k+1}) + r^{-2t'}\delta^0(p_{2k+2}). \quad (6)$$

Delete p_{2k+1} from the Eqs. (4) and (6), then,

$$\delta^0(p_{2k}) \geq \delta^0(p'_{2k}) + r^{-2t'}\delta^0(p'_{2k+1}) + r^{-2t'}\delta^0(p_{2k+2}). \quad (7)$$

Similarly, delete p_{2k} from the Eqs. (3) and (4), then,

$$\delta^0(p_{2k-1}) \geq r^{-2t'}\delta^0(p'_{2k-1}) + r^{-2t'}\delta^0(p_{2k+1}) + r^{-2t'}\delta^0(p'_{2k}) \quad (8)$$

From Eq. (7) and $\delta^0(p'_{2k}) > r^{-2t'}\delta^0(p'_{2k})$, we have

$$\delta^0(p_{2k}) > r^{-2t'}\delta^0(p'_{2k}) + r^{-2t'}\delta^0(p'_{2k+1}) + r^{-2t'}\delta^0(p_{2k+2}). \quad (9)$$

Take the sum of Eqs. (8) and (9) for $k = 1, 2, \ldots, m$, and multiply both sides by $r^{2t'}$, we obtain

$$r^{2t'} > \frac{\sum_{k=1}^{m}(\delta^0(p_{2k-1}) + \delta^0(p_{2k}) + 2\delta^0(p'_{2k-1}) + 2\delta^0(p'_{2k}))}{\sum_{k=1}^{m}(\delta^0(p_{2k-1}) + \delta^0(p_{2k}))}. \quad (10)$$

Since this is a necessary condition of $C \subset D$, a sufficient condition of $C \not\subset D$ is represented as

$$r^{2t'} \leq \frac{\sum_{k=1}^{m}(\delta^0(p_{2k-1}) + \delta^0(p_{2k}) + 2\delta^0(p'_{2k-1}) + 2\delta^0(p'_{2k}))}{\sum_{k=1}^{m}(\delta^0(p_{2k-1}) + \delta^0(p_{2k}))}. \quad (11)$$

Here we obtain the condition on r using K as follows:

$$r \leq K^{\frac{1}{2t'}}$$

□

Now we discuss the meaning of this condition. To guarantee that no cycle is created, we consider the minimum value of K. From $p_{2k-1} + p_{2k} > 0$ and $p'_{2k-1} + p'_{2k} > 0$, K takes the minimum value when $\sum_{k=1}^{m}(\delta^0(p'_{2k-1}) + \delta^0(p'_{2k}))$ is the minimum and $\sum_{k=1}^{m}(\delta^0(p_{2k-1}) + \delta^0(p_{2k}))$ is the maximum. Here, if we suppose that the range of metric is indicated by $m_{\min} = 1$ and $m_{\max} = 5$, and let $w = 10$ be the diameter of the network in hop count (i.e., the hop count of the longest path under the routing table), the minimum values of $\delta^0(p'_{2k-1})$ and $\delta^0(p'_{2k})$ are both 1. Also the maximum values of $\delta^0(p_{2k-1})$ and $\delta^0(p_{2k})$ are both 50. Hence,

$$K \geq \frac{2m + 2(50m)}{2(50m)} = 1.02$$

Now we assume that $t' = 1$ without loss of generality. Then to guarantee loop-freedom, $r \leq 1.02^{\frac{1}{2}} \approx 1.00995$ should be satisfied. It is concluded that in case of one-time metric change, every node can change its link metrics by about 1% if we suppose the metric range to be $m_{\max}/m_{\min} = 5$.

4.2 The Case of Periodical Metric Changes

In this section we give the condition of loop-freedom in case of the practical situation, i.e., case of periodical metric changes. When dynamic metrics are deployed in proactive link-state routing protocols, link metrics are propagated hop by hop. Thus, it takes more time to notify metric values to the farther nodes. This propagation delay should be considered when we design loop-free mechanisms for this situation. We assume that, in the base routing protocol, each node updates link metrics just before sending periodical link information messages so that new information massages always include new metric values. The message interval is usually not short enough to follow the real-time transition of wireless environment, e.g., in OLSR, TC message interval is 5 seconds by default.

Now, let t_{int} be the link information message interval and let w be the diameter of the network in hop count. Also, let r' be the allowed metric stretch per metric update, i.e., nodes can change metrics periodically at every t_{int} to the values in the safe range indicated by r'. Note that, when a metric is propagated, the expected time to wait in a node before the metric is sent to the next node is $\frac{t_{int}}{2}$, and thus the total time taken to propagate a metric throughout the network is $w\frac{t_{int}}{2}$. If we consider that t' is the time taken by metric propagation, i.e., $t' = \frac{wt_{int}}{2}$, this time t' indicates the range of metrics used simultaneously in the nodes of the network to compute their routing tables. Namely, each node uses the metrics generated in the time interval between $t - t'$ and t, where t is the current time. Thus, if we select any two nodes $u, v \in V$ in the network, the two metrics of link l memorized in u and v are both in the range of $r^{t'}$ in Eq. (1). Hence, the composition of two DAGs $D_u(d) \cup D_v(d)$ create no cycle if the condition on r in Theorem 1 is satisfied. This implies that Theorem 1 again gives a sufficient condition for loop-freedom for the case of periodical metric changes.

Here, we have $r^{t'} = r'^{\frac{t'}{t_{int}}} = r'^{\frac{w}{2}}$ from $t' = \frac{wt_{int}}{2}$, and thus Theorem 1 leads the loop-free condition on r' as follows:

$$r' \leq K^{\frac{1}{w}}.$$

Before considering the specific values of loop-free range, we have to show the loop-freedom formally. Note that the above discussion and Theorem 1 shows the case of only two DAGs computed from two different metric sets. Now we show that it is generalized into the case of more than two DAGs.

Theorem 2 Let $m_l^{(i)}(1 \leq i \leq N, N$ is the number of nodes in the network) be the metric of link $l \in E$ in the i-th metric set M_i and assume that $m_l^{(i)}r^{-t'} \leq m_l^{(j)} \leq m_l^{(i)}r^{t'}$ for every $1 \leq i, j \leq N$. Then, the sufficient condition of r to guarantee that $D = D_1 \cup D_2 \cup \ldots D_N$ does not include C is the following:

$$r \leq K^{\frac{1}{2t'}}$$

Proof: We again use Fig. 1 to refer the cycle C. We select the node list $n_1, n_2, \ldots, n_{2m}$ from C in which every node n_k satisfies the following conditions: (a) the shortest path p_k from n_k for d under some metric set M_i does not include the next node n_{k+1} in C, and (b) another shortest path $p'_k + p_{k+1}$ under another metric set M_j includes n_{k+1} in C. Let p'_k be the prefix of the latter path which is included in C. The worst case where the cycle is the most likely created is that all links in p_k take the minimum possible metric under M_i while it take the maximum possible metric under all the other metric sets $M_j(i \neq j)$. We have to consider only this worst case to guarantee C not to be included in D. Since the costs of a link under different metric sets can differ at most r^t in ratio, we can assign the metric of Theorem 1 without loss of generality, as follows: 1) the metric of p_k under M_i corresponds to $r^{-t}\delta^0(p_k)$ and that under M_j corresponds to $\delta^0(p_k)$. 2) the metric of p'_k and p_{k+1} under M_i corresponds to $\delta^0(p'_k)$ and $\delta^0(p_{k+1})$ (resp.), and under M_j corresponds to $r^t\delta^0(p'_k)$ and $r^t\delta^0(p_{k+1}$ (resp.). This correspondence leads to Eqs. (2) and (3) in Theorem 1, resulting in the same condition. □

Now we give the specific range values of loop-freedom. If we suppose $m_{\min} = 1$, $m_{\max} = 5$ and $w = 10$, then $r' \leq 1.00198 \approx 0.2\%$. In reference, if $w = 5$, $r' \leq 1.00787 \approx 0.8\%$. In case of $m_{\min} = 1$, $m_{\max} = 2$ and $w = 10$, $r' \leq 1.00489 \approx 0.5\%$.

One might think that this value is too small in practice. If the message interval is 5 seconds, then we can change the metric about 2.4% in a minute. In the future, if wireless bandwidth is expanded and the message interval of 1 second is allowed, then we can change metric about 12.6% in a minute. Even this might be difficult for practical use. However, fortunately, as shown in the next section, the safe range for practical use is possibly far larger than theory. Even if the theoretical value is not applied, this approach works effectively to reduce loops.

5. Traffic Simulation

5.1 Simulation Setup

We conducted a simulation experiment to evaluate the effect of LMR. The simulation is done with a network simulator Qualnet [17]. We implemented one of the most standard dynamic metric technique ETX [3] and LMR, by modifying OLSRv2-NIIGATA which is included in Qualnet 4.5. We compared two dynamic metrics, i.e., 'ETX' and 'ETX with LMR' in several traffic patterns and parameters. Our basic simulation set up is shown in **Fig. 2**. To compare the number of loops occurring and the throughput in multi-hop environment, we created mesh network with 25 stationary nodes on 1500 m x 1500 m field. The interval of two adjacent nodes is 300 m and the transmission power is 85 dB, so that only adjacent nodes of four directions can communicate with each other. We use 802.11 as wireless L2 protocol with 2 Mbps links. Flows go along the four diagonal lines, i.e.,

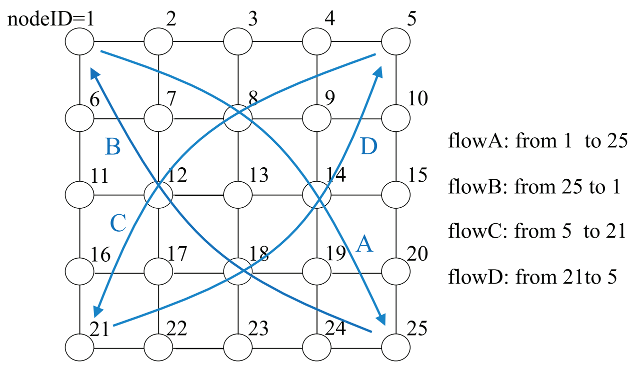

Fig. 2 The simulation scenario.

node 1 to 25, 25 to 1, 5 to 21, and 21 to 5. We use two types of traffic, CBR and FTP, in both the packet size is 512 bytes. In our scenario, we start transmitting flows after 1 minute from the simulation start, and stop it at the time of 6 minute, i.e., we transmit traffic during the period of the 5 minutes.

As for OLSR settings, the default value is used for hello interval and TC interval, i.e., 2 and 5 seconds, respectively. The validity time of hello is set as 20 seconds, i.e., a link fails only if 10 sequential hello messages are all lost. Since nodes are stationary, this setting improves the performance even for ETX without LMR. We use hello messages as ETX probe packets, and measures the number of hello message reception in the latest 20 seconds to compute ETX metrics. In every scenario we performed 30 simulations and the average values are used to give the results.

5.2 Results

In our first scenario, we transmit 20-80 kbps CBR traffic for flow A-D to see the throughput and the number of loop packets. The metric stretch r is fixed as 1.01. The result is shown in **Fig. 3**. The total throughput increases as the transmission rate rises, and about 70 kbps transmission would be the ceiling for it. The number of loop packets are increased when the transmission rate approaches to the ceiling point. The actual behavior of the traffic is that the ETX values goes larger and the communication paths are frequently changed among several paths when approaching the ceiling point.

The next scenario is that we fix CBR transmission rate at 40 kbps, and compare the performance of ETX and LMR with several metric stretch r between 1.01 and 1.40. The result is shown in **Fig. 4**. The total throughput decreases when the metric stretch r goes larger, and that of ETX is the worst among them. Also, the number of loop packets goes larger when r goes larger, and again that of ETX is the worst among them. Those results indicate that LMR works well to reduce loop packets. Note that this scenario is intended for studying the situation where the network is not saturated. (Transmission rate 40 kbps is lower than the ceiling point seen in Fig. 3.) The result shows that the performance improves as r decreases unless the network is saturated.

Next we consider the number of flow disruption, which is deeply related to the reliability of networks as an infrastructure. **Figure 5** and **Fig. 6** show the delivered packet number per second of the worst throughput case among 30 trials where $r = 1.01$ and CBR rate is 40 kbps. Figure 5 shows the result of ETX, and Fig. 6 shows that of ETX with LMR. These show that ETX experienced two severe flow disruptions in the short period of 5 minutes; it is clear that ETX with LMR supplies far more stable communications.

Figure 7 shows the summary of the number of flow disruption we have seen in Fig. 5 and Fig. 6, where the number and the length (in time) of disruptions are aggregated from all 30 trials. Here we define disruption as the period of time during which the number of received packets per second is less than 2. This result also shows that LMR with lower metric stretch r makes better performance and ETX makes the worst performance.

Figure 8 shows the result where we transmitted four FTP flows as flows A-D. This roughly shows similar result to the CBR case.

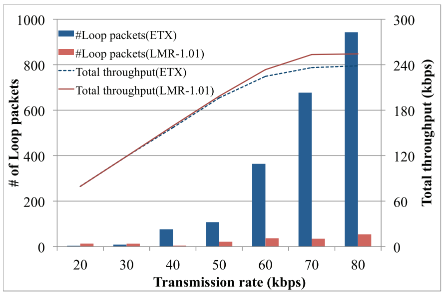

Fig. 3 Loops/throughput with various CBR rate.

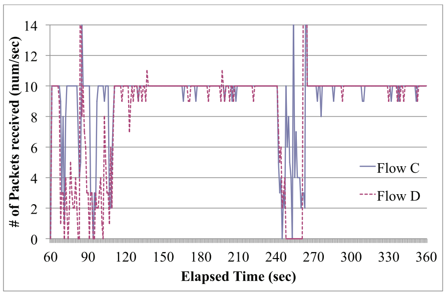

Fig. 5 Flow disruptions in ETX.

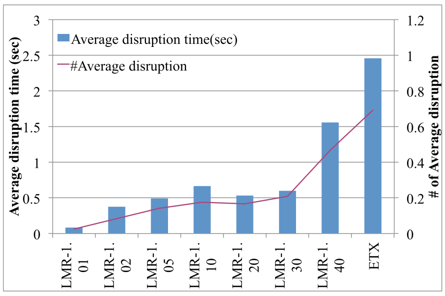

Fig. 7 Number and interval of flow disruption.

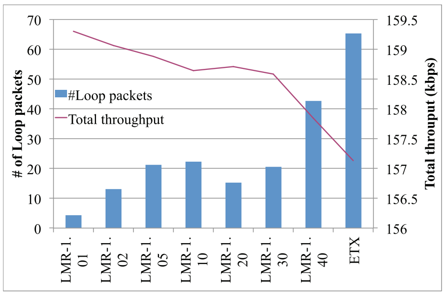

Fig. 4 Loops/throughput with various value of r.

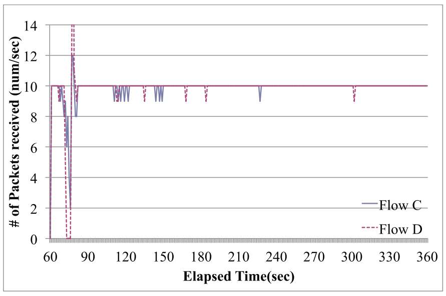

Fig. 6 Flow disruptions in ETX with LMR.

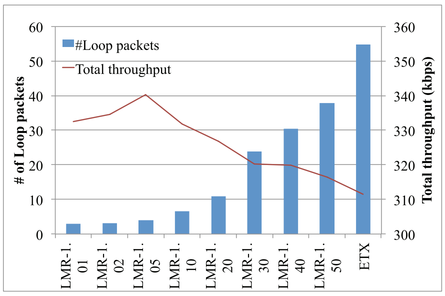

Fig. 8 Loops and throughput with FTP traffic.

It is interesting, however, that there is the peak in total throughput. It is inferred that the peak value comes from the trade-off between the effect of LMR's loop reduction and the ability of LMR to follow traffic fluctuations. Namely, when r goes larger than 1.05 looping degrades the throughput, and when r goes lower than 1.05 LMR's metric stretch prevents ETX from improving the throughput.

5.3 Discussion

From the simulation results, it is confirmed that LMR is effective in improving robustness against communication disruptions as well as network throughput. Although the theoretical value of metric stretch r which guarantees loop-freedom is too small to treat actual dynamics of link quality, it is shown that the larger value of r is sufficiently effective to reduce routing loops.

In the simulation, we observed many loops which cause not only metric change but also link failure due to loss of control messages. Especially in simulations of more than 60 kbps CBR traffic, many links failed and consequently loops are increased. In case of FTP traffic, we observe less link failure so that far higher throughput is measured, but nevertheless link failure causes considerable number of loops and flow disruption. Furthermore, loss of control messages cause delay of link metric propagation, which creates more loops. This implies that an important task to achieve disruption-free reliable WMN infrastructure is to protect control messages and links from failing, which would result in reducing loops.

In this simulation, we observed that the number of loops and the throughput improve as the metric stretch r decreases. Note that, however, this does not mean that the fixed metric is better than dynamic metric. Many past studies have verified the effectiveness of dynamic metrics. Although our CBR scenario does not show it explicitly, TCP scenario shows that there is the best value of r, which is 0.05. We observed that, when r is smaller than 0.05, congestion due to flow concentration gets severe and causes so many link cuts, which considerably degrades the throughput performance. On the other hand, as we see in the simulation results, large r causes packet loops that degrades the performance. The result of TCP scenario shows that there is the value of r that achieves the best balance between loops and congestion.

6. Real Evaluation

6.1 Implementation

We implemented LMR in note PCs and conducted an evaluation in an actual operating environment. We use Toshiba Dynabook SS RX2 SG120E/2W as the note PC and attached a NEC WL300NU-AG NIC that runs IEEE802.11n as shown in **Fig. 9**. Ubuntu Linux ver. 11.04 is installed in a USB flash memory, and the OS boots from it. We installed olsrd version 0.6.1 [18] in which ETX is implemented. We modified olsrd to implement LMR.

6.2 Evaluation Setup

We placed 6 note PCs in the 5th floor of the A-building of Faculty of Systems Engineering, Wakayama University. The map and the network topology are shown in **Fig. 10**. We use IEEE802.11n with 1 Mbps communication speed over channel 48 in 5 GHz band. Before the experiment, we cofirmed that no Wi-Fi station is working on the channels that interfere with channel 48. We generated two 500 Kbps CBR (Constant Bit Rate) flows from node a to b, and from b to a, for a 20 minutes period using packet generator iperf ver. 2.0.5 [19]. Packet size is set as 78 Bytes including UDP header.

We compares the performance of 'ETX' and 'ETX with LMR'. Metric stretch r is set to 1.05 and 1.2. As the performance indicators, we use throughput, the number of loop packets, the number of lost Hello messages, and the number of link cuts which are measured by Wireshark ver. 1.4.6 [20]. We executed 6 experi-

Fig. 9 Implementation.

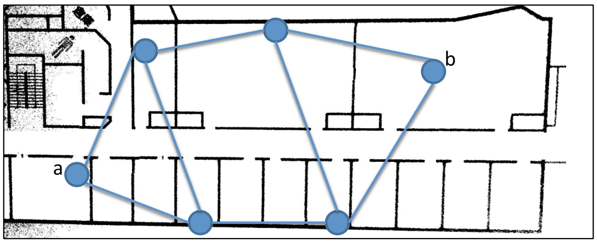

Fig. 10 Topology of experimental network.

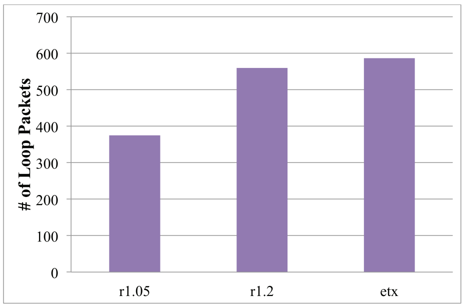

Fig. 11 Number of loops.

ments and compares the average of each performance measure. To measure the number of loop packets, we modified iperf to write a sequence number in the payload of each packet; we regard the packets that visit the same node more than once as loop packets. The number of lost Hello messages are measured by finding skipped sequence numbers in the log of olsrd. As for link cuts, we count the number of three successive loss of Hello messages since olsrd regards it as the link cut.

6.3 Results

Figure 11 and **Fig. 12** show the average throughput and the number of loops, respectively. The number of loop packets is the largest in ETX, and it is lower with LMR when the metric stretch r is lower. We also see that the throughput performance is correlated with the number of loops, i.e., LMR with lower stretch r performs better than others. These results show that LMR is also effective in reducing looping packets in real environment, and consequently in improving network performance.

For a detailed analysis, we show the number of Hello messages lost due to interference in **Fig. 13**. Surprisingly, larger number of Hello messages are lost in case of lower stretch factor r. This is

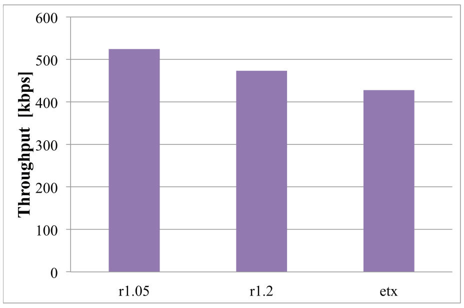

Fig. 12 Throughput.

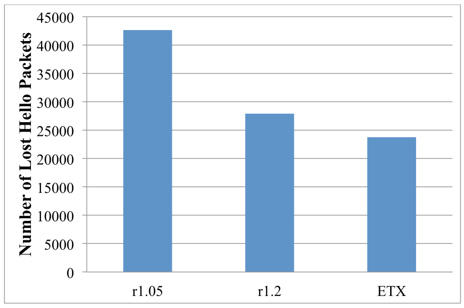

Fig. 13 Number of Hello drops.

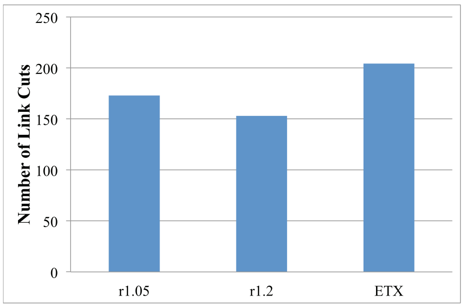

Fig. 14 Number of link cuts.

because ETX reacts more sensitively than LMR against collisions and changes the traffic state quickly to avoid loss of Hello messages. However, this does not explain why throughput is better with LMR than ETX. The reason is implied from the number of link cuts shown in **Fig. 14**, where the number of link cuts, i.e., the successive loss of Hellos, is larger in ETX than LMR. In ETX, because of the high dynamism of ETX, flows are easily injected to several specific paths, which easily causes the successive loss of more than 3 Hellos, i.e., link cuts. On the other hand, in LMR, despite a higher loss of Hello messages, the successive loss occurs less frequently than ETX due to more stable traffic state transition. Consequently, it is considered that the stability of LMR reduces loop packets, which improves the throughput performance despite of higher loss of Hello messages.

6.4 Discussion

We found that LMR also effectively works in real environments to reduce routing loops as well as to improve throughput. In real environment, we observed larger drops of Hello messages with LMR, although LMR performs better than ETX. This would be a trade-off between stability and dynamism in the network state. Although networks require dynamism to some extent, the performance of ETX is not good since ETX produces too much dynamism. On the other side, too little dynamism due to small of the stretch factor r causes severe congestion that results in loss of Hello messages and link cuts. Over the trade-off, LMR works as a safe limiter to suppress dynamism of network state brought about by link metrics such as ETX, which keep the communication performance within a practically allowable range.

7. Conclusion

In this paper we presented a new loop-free mechanism LMR for proactive link-state routing scheme as an extension of existing additive dynamic metrics. LMR is designed based on the discovery that temporary loops can be eliminated by limiting metric change ratio. The theoretical results clearly show that the loop-free threshold of the ratio depends on the minimum and the maximum values of the metric $m_{\min}$ and $m_{\max}$, and the diameter of the network in hop count. This is a new academic result that can be utilized in future routing protocols. However, through simulation and real evaluations, we found that the loop-free limitation of LMR is too small for the current link-state routing scheme to provide a sufficient dynamism to follow the topology and traffic transition of wireless mesh networks. This is due to heavy collision coming from current CSMA-based MAC protocol, which incurs large dynamism of routing metrics. Nevertheless, we also found that LMR still works effectively in the current routing scheme to reduce routing loops in both simulation and real environment. These results show that LMR effectively functions as a limiter on dynamism in a network state.

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