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LLD: Loop-free Link Metrics for Proactive Link-State Routing in Wireless Ad Hoc Networks

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1. Introduction

As wireless communication has become to be popular all over the world, the next promising network technology is the multi-hop wireless networks so called wireless ad hoc networks. Since wireless ad hoc networks require far lower cost to construct than wired networks, it is expected as technology to expand network coverage in both physical areas and applications. As infrastructure, wireless mesh networks (WMNs) (2) which consist of stationary nodes are considered to expand coverage of the broadband Internet. And further, with users' terminals such as PDAs, note PCs and mobile phones (mobile nodes), ad hoc networks will be more useful and flexible tools to enable further useful applications. Although many technical problems remain to be solved, the challenge to put ad hoc networks into practice is hopefully continuing.

One important issue on wireless ad hoc networks is how to supply stable and reliable communications between nodes over vulnerable wireless links. The current ad hoc networks adopt the same strategy as the traditional wired networks; nodes deploy a common routing protocol to recompute new paths in case of topology changes such as link failure. From this approach, currently four routing protocols AODV(3), DSR(4), OLSR(5) and TBRPF(6) have been standardized in IETF. Each of them adopts several mechanisms to handle ad hoc network specific properties such as mobility or wireless instability. They, however, basically compute the hop-count based shortest paths for destination nodes regardless of link state or quality.

Consequently, much work has been tried to improve communication quality by way of taking link stability and quality into account. In mobile scenario, since node mobility is a main factor which brings link breakage, the main concern to improve communication stability is to comprehend link duration. Many analytical results contributed to clarify the characteristics and the statistics of link duration from various points of view (8)(9)(11)(15)(16). Based on those knowledge, also several routing metrics are proposed to improve communication stability by using long lifetime links as communication paths (9)(10)(13)(18)(17)(19)(20)(21).

On the other hand, mainly for the network which consists of stationary nodes such as wireless mesh networks (WMN) (2), several link quality metrics are proposed (22)(23)(24)(26)(29). They are also deeply related to communication stability since link quality effects on communication speed or probability of disruption. In this area of literature, link qualities are defined as several link quality related measurements such as average transmission count, delay, or bandwidth to utilize links with the best availability. Also, load balancing is possibly included in the requirement of routing metrics since congestion may cause degradation of

link quality in WMNs. Several proposals actually include this point of view in their design of routing metrics.
It is, however, worth noting that none of above dynamic routing metric proposal takes routing loops into account. Routing loops is an important factor of route stability since they may make communications degraded and unstable in link state routing scheme such as OLSR. Routing loops occur due to propagation delay of metric information which causes temporary inconsistency of the routing tables among network nodes. Routing loops are well studied in the literature of wired networks and has been also recognized as harmful phenomenon which brings severe congestion and loss of wireless connectivity (33)(34)(35)(36). In wireless networks, due to interference the harm of congestion coming from routing loops goes far severer than wired networks (37). It is also important for wireless multihop networks to eliminate routing loops in order to stabilize communications.
In this article, we present a dynamic link stability metric called LLD (Loop-free Link Duration) which guarantees loop-freeness even against transition of metrics. Our dynamic metric LLD and its mechanisms are designed to improve stability of communications in wireless ad hoc networks with low-cost extension for existing proactive link-state routing schemes such as OLSR. Specifically, we introduce our dynamic metric as a simple function of time, and give theoretical analysis on the two instability factors: routing loops and path oscillation. Although LLD concentrates on only one aspect of mobility metrics, i.e., link duration in stable state, this will be a practical example of low-cost loop-free mechanisms in dynamic metric environments. To the best of our knowledge, LLD is the first loop-aware routing metric for wireless ad hoc networks.
The rest of this article is organized as follows: We first describe the literature of the related studies in Section 2. Then, we explain our dynamic metric LLD and its mechanisms in Section 3. In Section 4, we define the problem of Loop-freeness and give a theoretical result on the condition of loop-freeness. In Section 5, we give the simulation results on path oscillation problem and show that path oscillation can be suppressed in our scheme. We also give traffic simulation results in Section 6. Finally concluding remarks are given in Section 7.

2. Related work

In this Section we describe the literature of several research topics related to this article. We first describe related work on routing metrics for wireless mobile ad hoc networks, and then we go to routing metrics for wireless networks which consist of stationary nodes, called wireless mesh networks (WMNs). After that, we show the literature of the study for eliminating routing loops in dynamic routing protocols.

2.1 On mobile networks

In mobile ad hoc networks, mobility of nodes is the biggest factor of losing communication stability since mobility brings link disruption. Although new paths are recomputed by routing protocols deployed, temporary disruption of communications is not negligible when we consider stability of networks.
The natural idea to make communications stable as long as possible is to use stable links which have long residual lifetime. From this idea, much work is done to estimate the residual link lifetime to select stable links for each destination. One major approach for this is to grasp mobility statistics using several mobility models. (Description of major mobility models is shown in (7)) In fact, from empirical experiment in (8), it is reported that the breakage of long lifetime links are mostly brought from mobility (not from interference or congestion) and

the statistics on node degree and link lifetime observed are quite similar to the simulation result of typical mobility models such as Random WayPoint Model (RWP). In this context, Gerharz et al. (9) studied the distribution of link duration through simulations under several typical mobility models. They also estimated the average residual lifetime for the links of given age, and their simulation result showed that the residual lifetime estimation based next hop selection improves communication stability. Cheng et al. (10) proposed the routing metric based on the balance between route lifetime estimation and path length, and then compared the performance with shortest path routing. Further, Zhao et al. (11) focused on more practical factors on mobility models, i.e., they consider more accurate patterns of node movements and practical dynamics of transmission range, to estimate link statistics (on such as link lifetime) more accurately.

Wireless signal strength is also available to improve communication stability. In the early stage of the literature, simple signal strength based routing schemes such as SSA (Signal Stability Adaptive Routing) (12) are proposed. they classifies the links into 'strong' and 'weak' groups based on the measured signal strength, and a source node requests paths of only strong links first, and later allows weak links in on-demand routing schemes. Later, more sophisticated utilization of signal strength appears, e.g., Tickoo et al.(13) proposed a new routing metric RFC (Route Fragility Coefficient) based on relative speed of two terminals of a link estimated from the transition of wireless signal power observed. As another work in this category, Triviño-Cabrera et al. (14) proposed a path metric computed from signal strength based link metrics where, for instance, they try to choose the path which has the maximum value of minimum signal strength among all paths.

On the other side, since the amount of mobility is directly related to the link stability, the study of mobility metrics to measure the amount of performance effect coming from mobility. They measure several metrics in various mobility models and mobility levels to find proper mobility metrics. Yawut et al. (15) studied link duration (LD), link state change (LC: the number of link state change, e.g., link creation and deletion), and link stability (LS) defined as LD/LC under several scenarios. Qin et al. (16) studied node degree, average link duration and the number of link breakage that a node observed under several mobility models, and concluded that the number of link breakage observed can be used as a mobility metric.

Other than the studies shown above, several practical work proposed various routing metrics (used in the best path computation) which improves communication quality in mobile scenario. Zhao et al. proposed a routing metric called PARMA, which considers lower layer information such as physical layer link speed and estimated channel congestion. Karbaschi et al. (17) also proposed a cross-layer metric which considers link-quality and congestion. Cao et al. (18) proposed an integrated metric computed from hop counts, link load and power consumption. Guo et al. (20) proposed the method to predict three metrics of queuing delay, energy cost and link stability, and compute the optimal route heuristically by integrating those three metrics. Badis et al. presented QOLSR(21), a QoS extension of OLSR to operate multiple metric values, and provided so-called shortest-widest paths for best-effort traffic, which are the shortest paths computed under a kind of restriction on available bandwidth and delay.

2.2 On wireless mesh networks

Wireless Mesh Networks (WMNs) are regarded as a sort of ad hoc network in which nodes are stationary (2). WMNs are expected to be used as a infrastructure for wider areas where wired networks are hard to be built due to geometrical conditions or building cost.

In WMNs, the main factor of communication instability comes from the variation on wireless link quality and congestion since no mobility is assumed. Thus, much work tries to measure link quality as routing metrics through simple and low-cost measurement method.

The most widely used routing metric in WMN is ETX (Expected Transmission Count) (22) proposed by Couto et al., which is defined as the expected number of transmission required to deliver a packet. The ETX of a link is computed from the ratio of success transmissions which is measured by periodical probe messages sent on the link. ETX metric is the first routing metric which shows that routing metrics actually improve traffic throughput in MANETs against instability of wireless communications. Later, Draves et al. presented ETT (Expected Transmission Time) (23) which extends ETX by taking link speed into consideration as ETT= ETX$\frac{S}{B}$, where S is the packet size and B is the link bandwidth. WCETT was also proposed in the same paper (23), which takes bottleneck channel affection into account to compute path metrics under multi-channel environments. WCETT is computed as WCETT $= (1-\beta)\sum_{i=1}^{n}\mathrm{ETT}_i + \beta \max_{1\leq j\leq k} X_j$, where n is the number of hops on a routing path, k is the number of available channels for multi-radio operation, and $X_i = \sum_{\text{Hop } i \text{ on channel } j}\mathrm{ETT}_i$. Note that $\beta \max_{1\leq j\leq k} X_j$ represents the level of bottleneck channel affection.

Note that WCETT is not a link metric but a path metric. ("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. (24) 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 (25). Yang et al. also proposed a new path metric called MIC (Metric of Interference and Channel-switching) (24), which metric values can be decomposed to the isotonic metrics in a virtual network. This means that MIC is statically loop-free and is computed efficiently using the general shortest-path computation algorithms such as dijkstra's algorithm.

Note also that MIC (24) considers both intra-flow and inter-flow interference. In MIC, an interference-aware resource usage (IRU) of link l between nodes i and j using channel c is proposed as $\mathrm{IRU}_i = \mathrm{ETT}_i + N_{ij}(c)$, where $N_{ij}(c)$ is the number of nodes interfered with by node i and node j while using channel c. Also, to consider intra-flow interference, the channel switching cost (CSC) metric of node i is considered as $\mathrm{CSC}_i = w_1$ if incoming and outgoing hop of i in a routing path use different channels, and $\mathrm{CSC}_i = w_2$ otherwise, where $w_2 > w_1$. Then, MIC metric of a path p is represented by $MIC_p = \frac{1}{N\times\min(\mathrm{ETT})}\sum_{\text{link} l\in p} IRU_l + \sum_{\text{node} i\in p} CSC_i$, where N is the total number of nodes in the network.

There are several further proposals for this topic. For instance, Jin et al. (26) proposed a routing metric which considers the effect of hidden/exposed terminal interference. Also, Waharte et al. (27) proposed a routing metric which measures time to transmit a packet to its neighbor using a model based on the behavior of Wifi (IEEE 802.11) protocol.

From the other approach, several delay based metrics are proposed. Guo et al. presented a routing scheme called OLSR_NN (28) which based on prediction of delay measurement using the technique of neural networks. Murthy et al. presented LDAR (29), 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. Other delay based routing metrics are summarized in (30).

Among those current proposals on dynamic metrics for ad hoc networks and WMNs, there is no proposal which cares temporary routing loops, which brings us a severe congestion and interference. To improve communication stability in ad hoc networks, preventing routing loops should be regarded as one of the important issues.

2.3 On loop-free routing

Now let us take a look at loop-free mechanisms in dynamic routing schemes. In fact, routing loops are well investigated for wired networks and deeply related with dynamic metrics. Currently, deploying dynamic metrics in the Internet is unusual due to instability coming from changing paths. (It brings variation of bandwidth, delay, and so on which cause instability of communication throughput.) Dynamic metric schemes have been investigated, however, from the early stage of the Internet (31)(32). Their main object is to improve network performance, i.e., to improve network throughput and to avoid congestion, so that the effect of temporary routing loop formation is not considered.

The first loop-free routing scheme was presented as DUAL (33), which controls the sequence of routing tables to update when the topology (or metrics) changes in distance-vector routing schemes. Now DUAL is implemented in EIGRP routing protocol developed by Cisco systems. Later, Francois et al. (34) presented a loop-free link-state routing scheme from the similar strategy. They are always loop-free, however, since they require control messages for each topology change, the overhead is not sufficiently low for wireless ad hoc networks.

As another side, there are the studies on the safe (i.e., loop-free) range of metric modification (35)(36). They analyzed the case of changing at most one metric value simultaneously, and give an algorithm to compute the safe range of the value to be modified. They actually clarified an important property of routing loops, but it is not practical since they require a kind of central control not to allow changes of more than two metric values simultaneously.

To the best of our knowledge, LLD, which is proposed in this article, is the first loop-aware routing metric for wireless ad hoc networks. LLD is regarded as the method which follows the approach of "safe range" shown in (35)(36), and extends them into distributed network environment. Since this approach is low cost, LLD is suitable for wireless ad hoc networks.

3. Mechanisms and protocols of LLD

3.1 The dynamic metric of link stability

In this section, we describe the mechanisms of our metrics to extend proactive routing schemes such as OLSR (5). Normally in proactive routing, every node has a topology database of the network to compute the shortest path for each destination, where hop-counts are used as routing metrics.

Instead of hop-counts, we introduce dynamic link metrics which represent stability of links. In LLD routing scheme, it is considered that link stability is represented by the duration of time in which the link is in stable state, i.e., the longer a link stays stable, the smaller its metric becomes. Every link metric $\delta^t(l)$ of link l are managed by its directly connecting node with the following formula as long as the link is judged to be "stable."

$$\delta^t(l) = ab^t + c.$$

Here, t is time passed by since the link was born, and $b(0 < b < 1)$ is a ratio of metric decreased per unit time. We assume the same value of b for all links in a network. Then, $a + c$ is a initial metric and c is the value into which the metric finally converge. As for a and c, each link has its own values.

When a link is judged as "unstable," its metric is reset into the initial value, i.e., the value of time 0. This judgment (whether a link is unstable or not) should be done cautiously not to make a careless metric reset of stable links. For the judgment, we can use several metrics

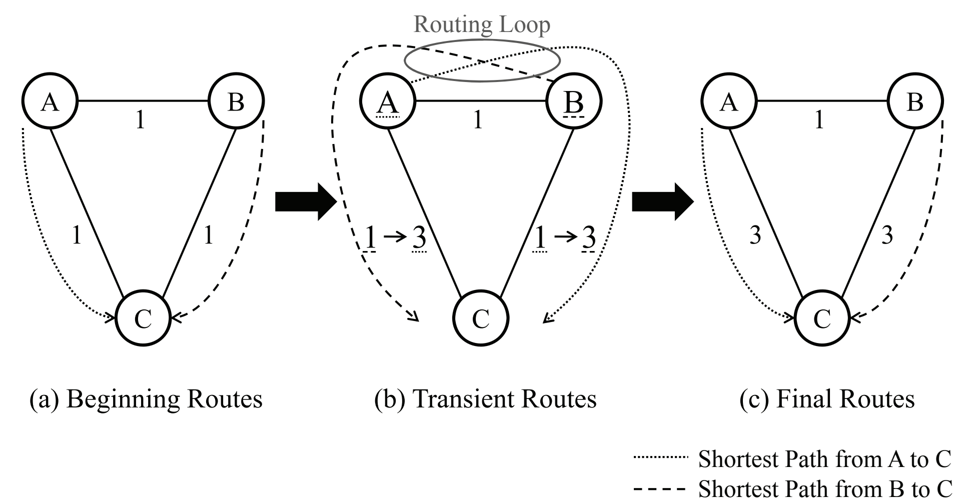

Fig. 1. An example of routing loops

proposed in the literature, e.g., transmission success ratio, physical signal power, and so on. However, since we now concentrate on theoretical aspect of loop-freeness, we do not discuss about this issue.

To say intuitively, a long-time stable link stays with a low metric whereas an unstable link (which metric is frequently reset) stays with high metric. As a result, traffic tends to use stable links from the nature of shortest-path computation so that communications become also stable.

Note that our metrics have to be synchronized periodically, i.e., the metrics of all links in every node's database are updated into the revised values periodically to prevent several different link metrics for a link used in route computation simultaneously. Namely, by periodical synchronization we prevent old metric values used in route computation, which usually occurs due to propagation delay of messages. We do this synchronization by flooding single synchronization message periodically.

3.2 Two issues on route stability in LLD

Routing loops and *path oscillation* are the two essential issues to be considered to realize stable communication in proactive routing. Especially, routing loops cause a severe instability problem so that it is strongly desired to be avoided. The loops occur when the topology (including metrics) of a network changes. During this period of time, two different routing tables computed from old and new topologies work together in the network so that a packet may loop among nodes if those routing tables are inconsistent. See Fig. 1 for instance. There are three nodes A, B and C in the network. The metrics of links (A, B), (A, C) and (B, C) are all 1 at the beginning so that the shortest paths from A and B to C go directly to C (Fig. 1(a)). Assume that the metrics of (A, C) and (B, C) change to 3 simultaneously. It is natural that finally the shortest paths from A and C is the same as the beginning state (shown in Fig.1(c)). In the transient state, however, routing loops possibly form due to propagation delay, where A regards the metrics of (A, C) and (B, C) as 3 and 1, respectively, while B does those as 1 and 3, respectively. This state is shown in Fig. 1(b), where the dotted and broken underlines indicate the metrics that A and B know. Such routing loops frequently occur in ad hoc networks and cause severe congestion and disruption of communications due to heavy packet loss.

On the other hand, the path oscillation problem is the problem that the path from a source to a destination changes frequently among several candidate paths. This also causes instability of communications. Both of those two problems (I.e., routing loops and path oscillation) are discussed in this article in the following sections.

Note that, when we treat loop-freeness, we assume the situation that the two events, i.e., (i) reset of metrics, and (ii) addition/deletion of links, do not occur. Note that this assumption is reasonable because those two events do not cause loops with high probability in typical situations. Considering that a link cause loops only when it is used in some shortest paths, event (i) causes loops only when the metric of the reset link has been low enough (otherwise, the link will not be used in shortest paths), and if the metric is low, the probability of resetting metric is considered also low. As for (ii), newly added links have so high metric values that they will not be used in shortest paths. Also, deleted links are supposed to be unstable with high probability so that their metrics is considered to be high and so will not be used in shortest paths.

As discussed above, as long as stable links keep stable with high probability, those two events generate loops with low probability. This indicates that loop-freeness in other (normal) situations is essential for stability of communications.

From the discussions above, the characteristic of the network to which our scheme is suitably applied is that: (1) stable links keeps stable with high probability and (2) there is sufficient number of stable links to construct stable-paths all over the network. Actually this situation is too realistic, but we have several networks which have similar characteristics, e.g., disaster networks which is expected to work as a simple infrastructure, or mixture network of wired and wireless links.

3.3 Synchronization mechanisms

As an extension to a proactive routing scheme, we have to support periodical update and synchronization of every link metric. The requirement of LLD for synchronization mechanism is that, at any point of time, every node uses the same metric value for a link to compute its routing table. (It is only when the time increases by synchronization message that two consequent metric values may be used simultaneously in a network.) Note that loop formation and path oscillation are easily affected by numerical errors of metric values so that the synchronization should be done accurately, i.e., metrics of different time (old and new) should not be used together in a path computation process. Also, message overhead should be low enough due to reduce communication overhead of wireless networks.

Further, for the synchronization mechanisms to be practical, it should be robust against several irregular cases. Specifically, it should endure (i) (not frequent) loss of messages, (ii) network division (including link/node deletion), and (iii) network integration (including link/node addition).

We need some consideration to meet this requirement. Of course, to flood every new metric value periodically over the network is not allowed since message overhead is too heavy for wireless ad hoc networks. Instead, we may take a method which adds fields of a, c and the generated time of links into link advertisement messages, and each node decreases all link metrics periodically according to each node's attached clock. This mechanism, however, have to assume accurate clock for all nodes. Moreover, joining even single wrong-time node may confuse routing. Alternatively, we can also flood a single "sync" message including sequence number into the network at each synchronization time. If we advertise the generated time of links in sequence number representation in link advertisement messages, every node is able to compute all links' current metric. There is, however, a problem when joining two different

networks with different sequence numbers.
Based on the above consideration, our synchronization mechanism is to send periodical sync message (with sequence numbers) which reaches only neighbor node. Also, we prepare fields of a, c and the generated time of links in link advertisement messages, where the link generated time should be expressed by the sequence number based on the sending node's sync messages. Under the behavior above, each node learns the timing to send sync messages so that the timing to send sync messages is synchronized in a network little by little. Thus finally all nodes send periodical sync messages almost simultaneously although some random factor should be considered to avoid interference among messages. Then, if each node changes the metrics of all links in its database every time the node send a synchronization message, the synchronization is done without problems.
This mechanism is able to keep correct metrics even after loss of control packets. There is no problem in both case of division and join of networks, although join process requires synchronization time to converge. Also, additional message overhead is very low if we use existing messages such as hello messages as sync messages in LLD. Note that this mechanism is only an example to do synchronization. But it shows that we can perform required synchronization of LLD in low cost.

4. Theoretical analysis for loop-freeness

4.1 Formulation of loop-freeness

Here we give a condition of synchronization time interval to be loop-free. We start with formulation of loop-freeness.
Let $G = \{V, E\}$ be a network, where V is a set of nodes and E is a set of links. For a pair of nodes $n_1, n_2 \in V$, we call they are *adjacent* if $(n_1, n_2) \in E$. A sequence of nodes $p = (n_1, n_2, \ldots, n_m)$ where $(n_k, n_{k+1}) \in E, k = 1, 2, \ldots, m-1$ are called *path*. The *metric* of link l at time t is denoted by $\delta^t(l) = a_l b^t + c_l$, where a, b and c is a real value and $0 < b < 1$. Note that the value of b must be common in a network but a and c is not. The metric of path p at time t is denoted in similar fashion by $\delta^t(p) = a_p b^t + c_p$, where $a_p = \sum_{l \in p} a_l$ and $c_p = \sum_{l \in p} c_l$. (Note that, theoretically, we can assume all links are generated simultaneously at time 0 without loss of generality. We have only to adjust the value of a_l to do so.) For a pair of nodes $s, d \in V$, the *shortest path* from s to d at time t is the path p that has the shortest value of $\delta^t(p)$.
Now we give the condition of loop-freeness. Routing loops are created only when the composition of the shortest paths computed from two succeeding states of metrics (i.e., before and after metrics change) creates cycles. Formally, let $D_1 = (V, E_1)$ and $D_2 = (V, E_2)$ be the DAGs generated from all the edges of the shortest paths computed from two succeeding states of metrics. (Note that since we consider equal-metric paths, shortest paths do not always form a tree but a DAG(Directed Acyclic Graph).) Then, it is clear that the sufficient condition to guarantee creation of no routing loops is as follows:

Proposition 1 *A sufficient condition to guarantee loop-freeness is that $D = D_1 \cup D_2 = (V, E_1 \cup E_2)$ has no cycle.*

4.2 Behavior of shortest path transition

A lemma is presented before the main result on loop-freeness. The following lemma shows an interesting property of shortest-path behavior under the metric function $\delta^t(l) = ab^t + c$.

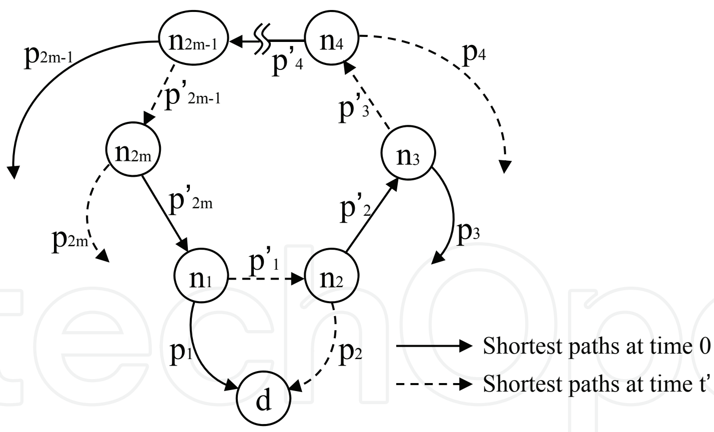

Fig. 2. The General Case of Routing Loops

Lemma 1 *Let p and p' be two paths departing from s to d where p is the shortest path at time 0. Then, $t' > 0$ exists such that p' is the shortest path from s to d at time t', if and only if $c_{p'} < c_p$. Further in this case, the length of two paths are reversed only once, i.e.,*

$$\delta^t(p) < \delta^t(p') \quad (0 \le t < t')$$
$$\delta^t(p) = \delta^t(p') \quad (t = t')$$
$$\delta^t(p) > \delta^t(p') \quad (t > t')$$

proof: Assume that $c_{p'} < c_p$. Then, at time $t = \infty$, p' becomes the shortest path since $\lim_{t\to\infty} \delta^t(p')(= c_{p'}) < \lim_{t\to\infty} \delta^t(p)(= c_p)$. Conversely, assume that $c_{p'} \ge c_p$. If $a_p \le a_{p'}$, then $\delta^t(p)(= a_p b^t + c_p) \le \delta^t(p')(= a_{p'} b^t + c_{p'})$ stands for arbitrary t. If $a_p > a_{p'}$, then $c_{p'} - c_p > a_p - a_{p'} > (a_p - a_{p'})b^t = a_p b^t + a_{p'} b^t$ stands from $\delta^0(p) < \delta^t(p')$. This formula leads $\delta^t(p) < \delta^t(p')$. Thus p' cannot be the shortest path for arbitrary t. As above, $c_{p'} < c_p$ is a necessary and sufficient condition for switching the shortest path.
Next, we show that the shortest paths switch only once. Consider t' such that $\delta^{t'}(p')(= a_{p'} b^{t'} + c_{p'}) = \delta^{t'}(p)(= a_p b^{t'} + c_p)$. This leads $c_p - c_{p'} = (a_{p'} - a_p)b^{t'}$. Since $0 < b < 1$ and $0 < c_p - c_{p'} < a_{p'} - a_p$, there is only one value t' which satisfies this formula. □

4.3 A condition for loop-freeness

Now we show the condition of loop-freeness. Fig. 2 shows the general situation of a routing loop created with paths for destination d. Without loss of generality, we assume this network has been synchronized at time 0 and the loop is generated in the next synchronization at time t'. The loop consists of both links in the shortest-path DAGs at time 0 and t'. So we can select a node n_1 from the loop, from which a link of time t' starts and at which a link of time 0 ends. Then, starting from n_1, we can divide the loop into a sequence of paths $p'_1, p'_2, \ldots, p'_{2m-1}, p'_{2m}$ where p'_{2k-1} and $p'_{2k} (0 < k \le m)$ consist of the links of time t' and 0, respectively. Let the starting nodes of p'_{2k} and p'_{2k-1} be n_{2k} and n_{2k-1}, respectively. Let the shortest path from n_{2k-1} to d at time 0 be p_{2k-1} and the shortest path from n_{2k} to d at time t' be p_{2k}. In this situation, the next statement stands:

Theorem 1 *Assume that a network synchronizes at time* 0 *and subsequently synchronizes at time* t'*. Then, a sufficient condition of* t' *to be loop-free is the following:*

$$t' < \frac{\log \frac{\sum_{k=1}^{m}(c_{2k-1}-c'_{2k-1}-c_{2k})}{\sum_{k=1}^{m}(\delta^0(p'_{2k-1})+\delta^0(p'_{2k})+c_{2k-1}-c'_{2k-1}-c_{2k})}}{\log b}$$

proof: The following formula stands at n_{2k-1}.

$$\delta^t(p_{2k-1}) > \delta^t(p'_{2k-1}) + \delta^t p_{2k} \tag{1}$$

For a path p, its metric is denoted by $\delta^t(p) = ab^t + c = (\delta^0(p) - c)b^t + c)$, Hence,

$$\delta^0(p'_{2k-1}) < \delta^0(p_{2k-1}) - \delta^0(p_{2k}) + \frac{(1-b^t)}{b^t}(c_{2k-1} - c'_{2k-1} - c_{2k}) \tag{2}$$

Similarly, the following formula stands at n_{2k}.

$$\delta^0(p'_{2k}) < \delta^0(p_{2k}) - \delta^0(p_{2k+1}) \tag{3}$$

Summing formulas (2) and (3) for $n_1, n_2, \ldots, n_{2m}$, we obtain

$$\sum_{k=1}^{m}(\delta^0(p'_{2k-1}) + \delta^0(p'_{2k})) < \frac{1-b^t}{b^t}\sum_{k=1}^{m}(c_{2k-1} - c'_{2k-1} - c_{2k}) \tag{4}$$

Since formula (4) is a necessary condition of creating loops, the following formula is a sufficient condition to be loop-free.

$$\sum_{k=1}^{m}(\delta^0(p'_{2k-1}) + \delta^0(p'_{2k})) \geq \frac{1-b^t}{b^t}\sum_{k=1}^{m}(c_{2k-1} - c'_{2k-1} - c_{2k}) \tag{5}$$

Transforming the formula (5) in respect of b^t, we obtain

$$b^{t'} > \frac{\sum_{k=1}^{m}(c_{2k-1} - c'_{2k-1} - c_{2k})}{\sum_{k=1}^{m}(\delta^0(p'_{2k-1}) + \delta^0(p'_{2k}) + c_{2k-1} - c'_{2k-1} - c_{2k})} \tag{6}$$

For $0 < b < 1$ and $0 <$ the right side of (6) < 1, the following conclusion is obtained.

$$t' < \frac{\log \frac{\sum_{k=1}^{m} c_{2k-1}-c'_{2k-1}-c_{2k}}{\sum_{k=1}^{m}\delta^0(p'_{2k-1})+\delta^0(p'_{2k})+c_{2k-1}-c'_{2k-1}-c_{2k}}}{\log b}$$

□

Now we discuss the meaning of this condition. For instance, suppose the situation where $a = 1000$ for all links and metrics converge to $c + 0.5$ when 1 week (10080 minutes) past. In this case, $b = 0.9992462$ if the unit of time is "minutes." Also, suppose the diameter of the network, which we define in this paper as the maximum hop-count of shortest paths, is at most 20. And c for each link takes a value between 10 and 50. In this situation, we consider the maximum value of the following K:

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

Here, $c_{2k-1} - c'_{2k-1} - c_{2k} > 0$ from *Lemma 1*, and $\delta^0(p'_{2k-1}) + \delta^0(p'_{2k}) > 0$. Thus K takes the maximum value when $\delta^0(p'_{2k-1}) + \delta^0(p'_{2k-1})$ takes the minimum and $c_{2k-1} - c'_{2k-1} - c_{2k}$ takes the maximum value. In this situation, the minimum values of $\delta^0(p'_{2k-1})$ and $\delta^0(p'_{2k-1})$ are both 10, and the maximum value of $c_{2k-1} - c'_{2k-1} - c_{2k}$ is $50 * 20 - 10 - 10 = 980$, hence,

$$K \leq \frac{(980m)}{(20m) + (980m)} = 0.98$$

Therefore, since $0 < b < 1$ and $0 < K < 1$,

$$t' < \frac{\log 0.98}{\log 0.9992462} = 26.79104797 \leq \frac{\log K}{\log b}$$

As shown above, the proposed scheme is loop-free if the synchronization interval is less than 26.7 minutes. For reference, if every link takes the same value of $c = 10$, the upper bound of t to be loop-free is 139.71982 minutes. Also, if we consider faster convergence such as 1 day instead of 1 week, the upper bound is merely $\frac{1}{7}$ of the above. Further, in this situation, if we always increment t by 1 in every synchronization, the condition $b > 0.9$ guarantees loop-freeness.

5. Preventing path oscillation

5.1 Rounding errors and path oscillation

In the theoretical analysis, we can assume that metrics are real values. Under this assumption, *Lemma 1* guarantees that path oscillation does not occur. However, in practice, values should be represented in computers by a finite length of bits. In fact, in our scheme, the rounding errors coming from this can cause severe path oscillation. In this section we describe the problem and solution for it.

Path oscillation between two paths occurs when the metrics of those two paths are very close. If we consider the case of using integer values as metrics, the range of possible rounding error per link is from -0.5 to $+0.5$. If a path has k links, its rounding error is from $-0.5k$ to $+0.5k$. Therefore, if metrics of two paths are closer than the each other's error range, frequent path oscillation will occur with high possibility.

As a solution, we use floating-point numbers (38) to represent metrics. Floating-point numbers have a useful property that when a value is smaller, the rounding error also becomes smaller. Since, in our metrics, the difference of metrics between two paths goes smaller as time passes, this property is so convenient. As we present later, floating-point numbers truly suppress the oscillation.

Here, note that there is a small problem. The variable c in the metric formula would have an integer value in many cases so that the range of rounding errors stops to go smaller. As a result, oscillation may occur when the path metrics become to be very small values. In order to suppress this kind of oscillation, we enforce to converge metrics into c when ab^t becomes sufficiently small, e.g., such as 0.5.

5.2 Simulation results on path oscillation

To measure how many times paths oscillate, we prepare the simulation scenario in which oscillation will likely to occur the most frequently. We suppose two paths which have the same number of links, have the same source and the destination node, have almost the same metrics, and have the same metric to converge. Fig. 3 is a snapshot of an example situation.

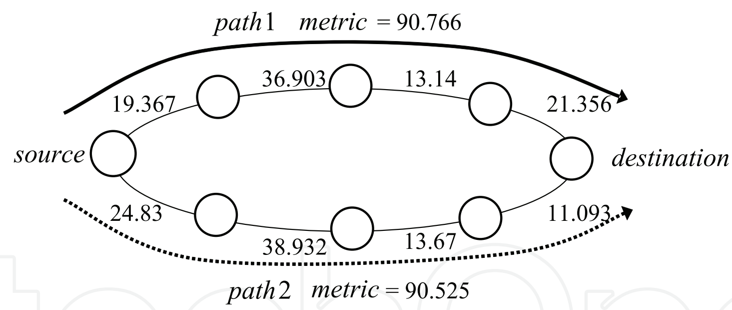

Fig. 3. Simulation Scenario

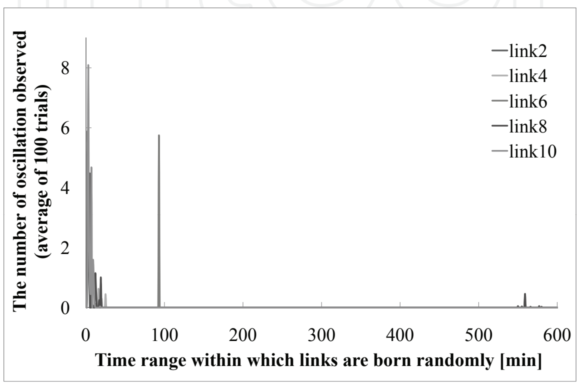

Fig. 4. The Result in Case of Using Single-precision Floating Points

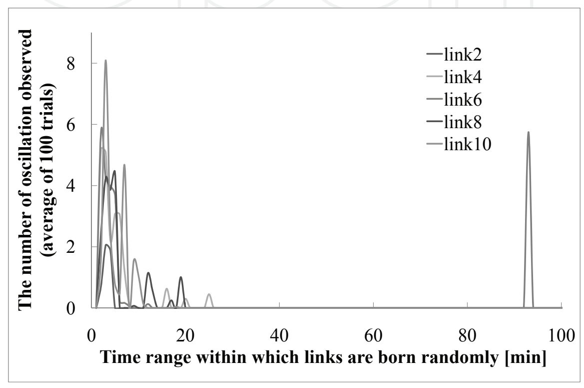

Fig. 5. Zooming Fig. 4 of first 100 minutes

Specifically, we set $a = 1000$ and $c = 20$ for all links, and set $b \simeq 0.9992462$. Namely, the initial metric of every link is 1020 and it takes a week (10080 minutes) to converge into 20.5. As mentioned previously, a metric is enforced to be 20 if the metric become less than 20.5. We assume SyncInterval is 1 (minute) so that path computation is invoked every 1 minute. This is far severe condition than usual. Note that if the result is safe in this condition, every other integer values of SyncInterval are guaranteed to be safe. We test the cases of 2 to 10 links included in each of the two paths, and for each case we generate the links at almost the same time, i.e., we randomly generate links within the time range of 1 to 30 minutes. Every case is tested 100 times and we measure the average number of oscillation occurred.

In Fig. 4, we show the result of the case that metrics are represented by single-precision floating point (32 bits) defined in (38). Although we observe some accidental oscillations (e.g., around 90 minutes of the time range), the number is totally small and practically permissible. There is a trend that the number of oscillations arises when the time range is small, but has no relation with the number of links. As another result, in case of applying double-precision floating point (64bits), we do not observe any oscillation at all. For reference, when the metric to converge is different between two paths even by 1, no oscillation is observed with single-precision floating point (32bits), either. We conclude that floating-point representation can suppress the oscillation.

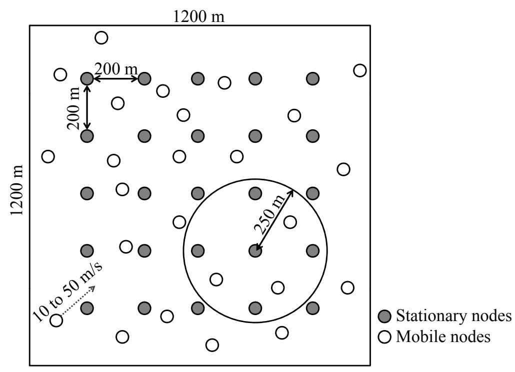

Fig. 6. Traffic Simulation Scenario

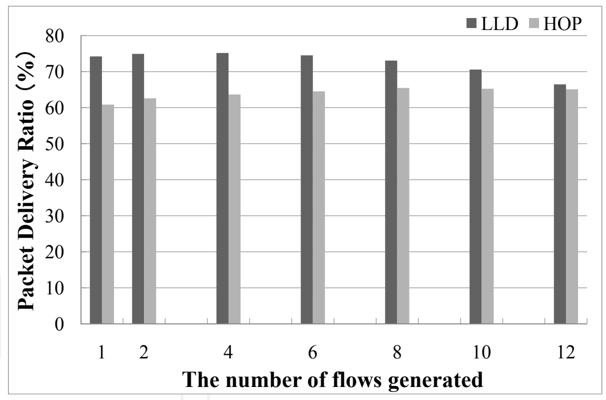

Fig. 7. Packet Delivery Ratio

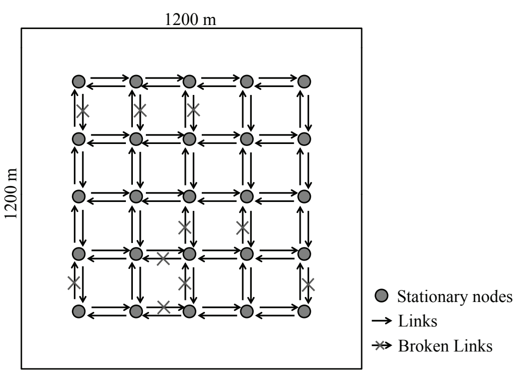

Fig. 8. Link State in 8 Flows Scenario

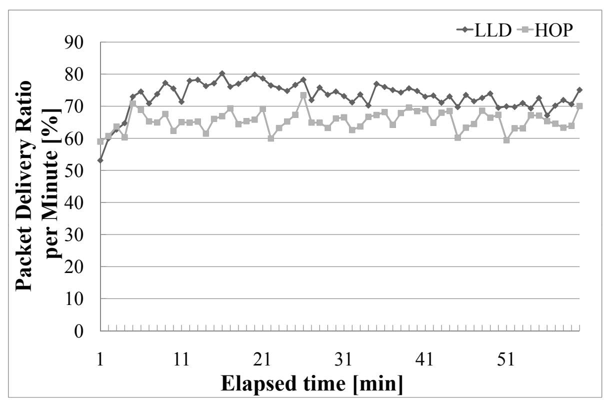

Fig. 9. Delivery Ratio per Minute

6. Traffic simulation

6.1 Simulation scenario

We compared the performance of LLD with conventional hop-count routing (HOP) through traffic simulation using NS-2 ver.2.29(39). We use UM-OLSR ver.0.8.8(40) for the base OLSR module and modify it to implement LLD. Note that the synchronization mechanism is not actually implemented, i.e., time synchronization is done using global variables in C language. Namely we assume that the synchronization mechanism works ideally.

Simulation scenario is illustrated in Fig. 6. To measure the communication performance in the network with both stable links and unstable links, we prepare 25 stationary nodes and 25 mobile nodes i.e., the links between two stationary nodes are regarded as stable, and others are relatively unstable. The field size is 1200m x 1200m and the stationary nodes are placed to form 5 x 5 grid where every interval of adjacent nodes is 200m and the communication range is set as 250m. The moving pattern of mobile nodes is generated by BonnMotion(41) to follow Random Way Point (RWP) Mobility Model. The moving speed is randomly determined between 10.0 m/s and 50.0 m/s. Those nodes communicate with each other via Wifi (IEEE 802.11) of 2Mbps bandwidth. Total simulation time is set as 1 hour.

LLD parameter is set as $a = 1000$, $b = 0.9$ and $c = 1$ for all nodes. Synchronization time interval is set as 1 minute so that every node updates all the link metrics every 1 minute and recompute

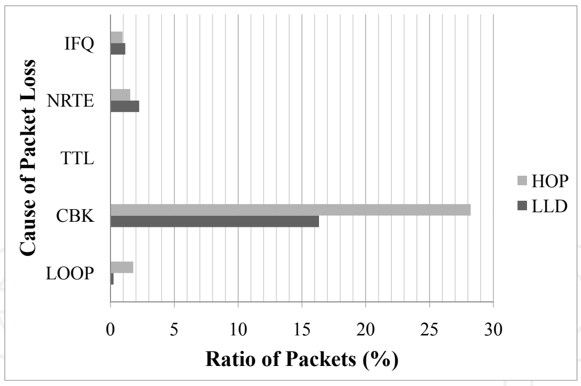

Fig. 10. Packet Loss Specification (4 Flows)

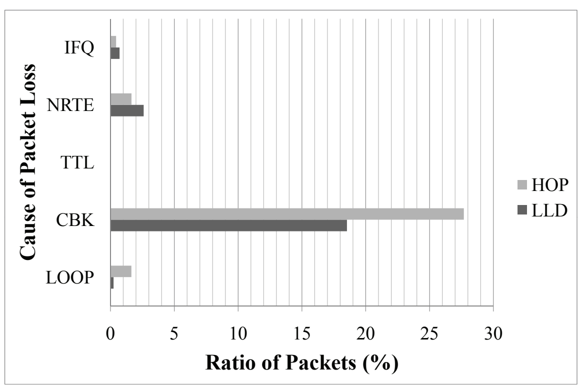

Fig. 11. Packet Loss Specification (8 Flows)

its routing table. Note that we set $b = 0.9$, which is the minimum value of b to guarantee loop-freeness in the network where synchronization time interval is 1 min, maximum hop count among all possible paths (the diameter of the network) is 20, and c takes a common value over the network. For the loop-free condition of b, see Section 4.

In our traffic scenario, several 10kbps CBR (Constant Bit Rate) flows with packet size of 512 bytes are generated between two randomly selected mobile nodes. We compare the communication performance between LLD and HOP by taking the average of 4 trials under variation of the number of flows generated.

6.2 Results of traffic simulation

Fig. 7 shows the packet delivery ratio for each number of flows 1, 2, 4, 6, 8, 10, and 12. When the number of flow is low enough (i.e., 1, 2, and 4), LLD keeps more than 10% higher delivery ratio than HOP. This is because LLD tends to use stable links (which connects two stationary nodes) to support stable communications, resulting in low probability to meet unavailable links. However, as the number of flows goes higher the difference of the performance goes smaller. This result comes from the property of LLD that traffic tends to be concentrated on specific stable links, which brings link breakage to increase loss of packets. For this link situation, see Fig. 8 which shows the state of 8 flows LLD scenario at 1800 second. As is seen in this figure, always several links are broken in such congested state.

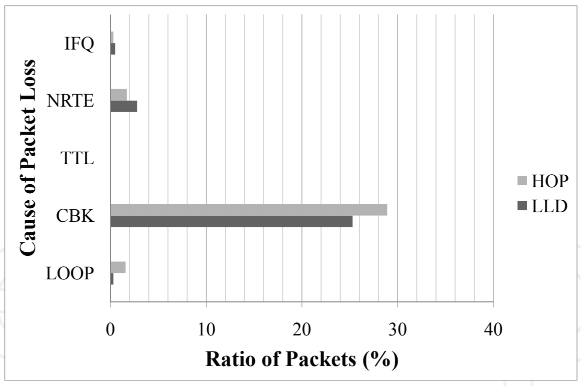

Fig. 12. Packet Loss Specification (12 Flows)

Fig. 9 shows the transition of packet delivery ratio with time course in the 8 flows scenario. Although in the first few minutes the difference are hardly seen since there are not enough difference in metrics between stable and unstable links, after that differences are constantly seen between LLD and HOP. It is found that LLD delivery ratio gradually decreased little by little, which we infer is the effect comes from the breakage of stable links.

Fig. 10-12 shows the specification of drop packets for possible drop reasons in the 4, 8 and 12 flows scenarios. Each loss ratio is represented as the value out of all transmitted packets in the 1-hour scenario. There are five reasons where IFQ is the loss coming from sending queue overflow, NRTE is the loss of no route found in the routing table, TTL is the loss from expiration of TTL (time to live) counter, CBK is the loss from radio interference, and LOOP is the dropped packets when they return to their source nodes.

From the results, we find that the ratio of looping loss (LOOP) is significantly decreased in LLD in comparison with HOP. Note that there are still a little looping packets in LLD although we use the value $b = 0.9$ which guarantees loop-freeness; the reason of the looping is considered link breakage due to radio interference. Note that even in the 4 flow (low load) scenario considerable packets are lost by radio interference (CBK).

The main difference between LLD and HOP is found in CBK. This difference includes not only normal radio interference but also that generated by looping packets. Since it is natural that normal interference between LLD and HOP will not differ considerably, the difference surely comes from looping packets. Consequently, we conclude that LLD improves both stability and throughput of communications by decreasing looping packets.

Incidentally, we found that the difference of CBK between LLD and HOP goes closer as the number of flows (traffic load) increases. This implies that LLD is not good at traffic capacity since LLD tries to concentrate traffic on only stable links. The load balancing performance would be one of the drawbacks of LLD.

7. Concluding remarks

We presented a new dynamic link stability metrics which achieves loop-freeness throughout dynamic metric transition. We gave a theoretical analysis on the condition of loop-freeness, and through simulations we presented that the instability coming from path oscillation can be suppressed by applying floating-point representation of metrics. Further, we presented a traffic simulation result in which LLD improved communication stability unless link load is too high. I wish our new strategy of loop-free routing suggests a new viewpoint of mobility metric in proactive routing schemes.

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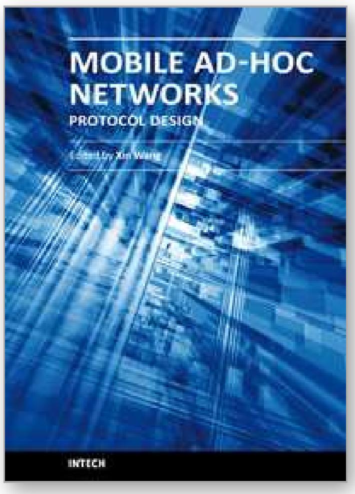

Mobile Ad-Hoc Networks: Protocol Design

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Being infrastructure-less and without central administration control, wireless ad-hoc networking is playing a more and more important role in extending the coverage of traditional wireless infrastructure (cellular networks, wireless LAN, etc). This book includes state-of-the-art techniques and solutions for wireless ad-hoc networks. It focuses on the following topics in ad-hoc networks: quality-of-service and video communication, routing protocol and cross-layer design. A few interesting problems about security and delay-tolerant networks are also discussed. This book is targeted to provide network engineers and researchers with design guidelines for large scale wireless ad hoc networks.

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