

On the Stability of Load Adaptive Routing Over Wireless Community Mesh and Sensor Networks

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Abstract— Wireless mesh networks are increasingly deployed as a flexible and low-cost alternative for providing wireless services for a variety of applications including community mesh networking, medical applications, and disaster ad hoc communications, sensor and IoT applications. However, challenges remain such as interference, contention, load imbalance, and congestion. To address these issues, previous work employ load adaptive routing based on load sensitive routing metrics. On the other hand, such approach does not immediately improve network performance because the load estimates used to choose routes are themselves affected by the resulting routing changes in a cyclical manner resulting to oscillation. Although this is not a new phenomenon and has been studied in wired networks, it has not been investigated extensively in wireless mesh and/or sensor networks. We present these instabilities and how they pose performance, security, and energy issues to these networks. Accordingly, we present a feedback-aware mapping system called FARM that handles these instabilities in a manner analogous to a control system with feedback control. Results show that FARM stabilizes routes that improves network performance in throughput, delay, energy efficiency, and security.

Keywords— wireless mesh networks, sensor networks, load adaptive, routing, and routing stability.

I. INTRODUCTION

A large percentage of cooperative community networks in the future are expected to be formed through community-based wireless mesh networks (WMN) [1]–[4]. Current routing metrics, such as hop counts, used for routing in wireless mesh networks unfortunately will not be able to scale up to the projected sizes of large community networks. With increase in size, so are challenges such as interference, contention, load imbalance, and congestion. As load increases and congestion builds up, network throughput decreases significantly. To address these issues, previous work employed load adaptive routing based on load sensitive routing metrics [5]–[9]. However, such approach does not immediately improve network performance because the load estimates used to choose routes are themselves affected by the resulting routing changes in a cyclical manner resulting to oscillation [10]. Although this is not a new phenomenon and has been studied in wired networks [11], it has not been investigated extensively in wireless mesh and sensor networks. Our investigations show other instabilities in wireless mesh networks such as security and energy issues that are not present in wired networks. To the best of our knowledge, these issues have not been reported in the literature and should prove useful in the research community.

Accordingly, this work presents a simulation test bed and a figure of merit called forward-delay product for studying the load-adaptive behavior and revealing the (in)effectiveness respectively of a proposed load-aware routing metric. The test bed has enough space for load-adaptive routing to maneuver around in the absence and presence of congestion in the network, thus exposing its instabilities. On the other hand, the forward-delay product relates to the amount of traffic that may be in transit across the network, and could be huge should routes oscillates badly. This metric should come handy when comparing

energy efficiency and stability of different load-adaptive routing schemes in wireless mesh networks. Ultimately, we also present a feedback aware mapping (FARM) system that handles the above mentioned routing instabilities in a manner analogous to a control system with feedback control. Extensive simulations show that FARM stabilizes routes improving network performance in throughput, delay, energy efficiency, and security.

The rest of the paper is organised as follows. Section II discusses the motivation and related work. Section III reports on the stability issues we found in load adaptive routing. Section IV introduces FARM, our subsequent approach to integrate stability control with any load-sensing technique and reports on its ability to stabilize routes. Finally, Section V summarizes our key findings, and maps the road ahead.

II. MOTIVATION AND RELATED WORK

Directly replacing currently used hop count metrics with load-aware routing metrics would not immediately improve network performance because the load estimates used to choose routes are themselves affected by the route choices with feedback effects [12], [13], [6]. That is, the use of a traffic flow for a less busy path to send traffic increases its busyness level. Then, at the next routing computation, that path no longer becomes the best path towards the destination, and another path is found. In turn, usage of the new path increases its busyness level making it less attractive route. This process continues in a cycle resulting to route flapping or oscillation.

One way to address this issue is to make nodes unresponsive to the traffic they themselves induced [6]. However, this approach leads to inaccuracies of actual channel load computation that load distribution is not always achieved [14], defeating the purpose of load balancing. On the other hand, using on-demand routing protocols instead of proactive routing ones is also possible [12]. On demand routing protocols do not recompute for the route between a pair of source and destination once it has been established, unless there is a link breakage [15]. Hence, with this kind of routing protocol, load changes do not lead to route re-computation that may lead to oscillation. On the contrary, the stabilizing effect is achieved at the expense of loss of sensitivity to traffic load changes. Further, in WMNs, nodes get occasional disconnection due to interference, noise, or channel fading [16]. Thus, even adhoc routing protocols, from time to time, recompute routes that may result to route oscillations.

Furthermore, the above-mentioned solutions are meant to control routing oscillations alone. They do not address other forms of routing instability like the inability of the routing algorithm to converge or its tendency to build routes with loops due to the presence of zero or near-zero weights of the load metric (see Section III). In this work, we address these issues.

III. ROUTING STABILITY ISSUES

To expose the behavior of a load-adaptive routing in the presence and absence of congestion, our investigation used a simulation test bed consisting of a mesh network composed of eighty-one (81) 802.11 wireless nodes uniformly distributed in an 1160×1160 square meter area (see Figure 1). To avoid the effects of performance anomalies exhibited by IEEE 802.11 devices in

the presence of other wireless devices operating at different nominal bit rates [17], [18], all wireless nodes were set to operate at the basic rate of 1Mbps where routing and topology control packets are also transmitted [18]. We also set the distance between devices such that the transmission range is within single hop.

Although in reality, wireless nodes are randomly placed, this work used a uniformly distributed topology so that all regions of the topology are covered, thus, expose better the route flapping behavior when using load-adaptive routing metrics. This topology runs in network simulator 2 (ns2) [19], with the OLSR extension as used in [20].

Our experiment specifically tested how a load-aware metric, called channel load metric or CLM [21], directed traffic across the network in the presence and absence of congested regions compared to the commonly used hop count based routing [15] metrics. That is, The main traffic flow (from node 0 to node 80 in Figure 1) sent 100 kbps of constant bit rate (CBR) traffic over UDP with a packet size of 1000 bytes. The user datagram protocol (UDP)[22] was used instead of the more commonly used transmission control protocol (TCP)[22]. TCP's congestion control may interfere with the load adaptiveness of the metric once the traffic gets very heavy, thus affecting the accuracy of our results.

Finally, an interfering traffic is set between node 40 and 48, and should veer the path of the main flow away from the center. This traffic between nodes 40 and 48 in Figure 1 varied from 0, 50, 100, 150, 200, 300, 400, until 450 kbps.

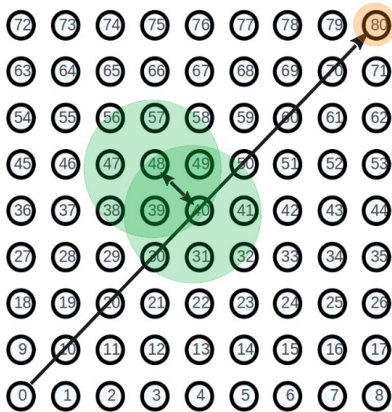


Figure 1: The testbed: a WMN with node 0 sends traffic to node 80 while nodes 48 and 49 congest the center.

A. Performance Issues

Figure 2 shows the CLM's performance with respect to hop count. Although the CLM-based routing veered the main traffic away from the loaded center region, in most of the scenarios it did not perform better than hop count in terms of throughput and packet delay. The worst scenario occurred when there was no interfering traffic at the center of the mesh network. In this scenario, on the average, the received throughput achieved by CLM-based routing was 37% less and the packet delay was 52% longer than those achieved in hop count based routing. This performance degradation has been reported due to oscillation alone [6], [12], [14], however our simulations showed that this is rather due to the inability of the routing algorithm to converge or to its tendency to build routing loops.

The routes behaved this way because of the zero or near-zero load weights for idle regions. In this case, when a node sent traffic towards a particular destination, the channel load weights of the regions along the path was relatively much greater than the zero or near-zero load weights of the idle regions. Consequently, the idle regions became better paths. The cost of the paths through the idle regions remained better, even if the route went

back and forth in a loop within a set nodes, than the cost of the path where the current traffic was traversing. Had the cost of each hop not been negligible in comparison with the path being traversed by the traffic flow, each cycle of the loop would have been more expensive in the computation of the path cost and another less cost path with less or no loop would have been found.

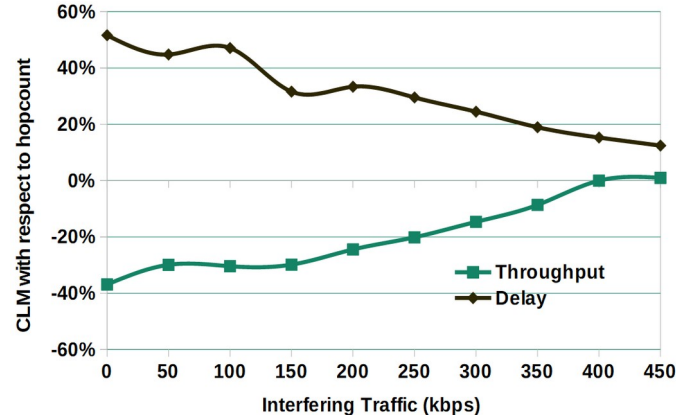


Figure 2: Performance comparison of CLM with respect to hop count based routing in terms of average received throughput and packet delay.

Table 1: CLM and Hop Count Behavior Comparison at 0 kbps Interfering Traffic

Metric Used	Sending Rate	Receive Rate	Ave Delay	Forward - Delay Product	Network Drop Rate	Participating Nodes
CLM	100 kbps	62 kbps	127 ms	40.3 Mbits	252 kbps	80
Hop count	100kbps	99 kbps	84 ms	10.5 Mbits	53 kbps	17
CLM wrt hop count	0	37% (less)	52% (longer)	283%	379%	283.00 %

B. Energy efficiency Issues

Although our target mesh network have nodes with stable source of power, the results of the experiment can be used to show how an untuned load-aware and adaptive routing metric could pose serious problems to wireless networks that are power limited like wireless sensor networks [23]. When the routing instability and oscillation is severe enough, more mesh nodes will participate in forwarding packets than what is necessary. As an illustration, in the 0kbps scenario, where the interfering traffic was non-existent, simulations results show that routing based on CLM metric practically spread the traffic across the network. On the average, the scenario that used CLM metric had all the nodes except the destination node participated in forwarding packets, 80 nodes out of 81 nodes. While the scenario that used hop count metric, around only 17 nodes participated in forwarding traffic, i.e. the nodes along the diagonal path from node 0 to node 80 (see Figure 1). With CLM-based routing, the network, on the average, forwarded 1318 kbps or 60% more than the 826 kbps for hop count based routing (Table 1). This result suggests that when there are no other communication going on in the mesh network, moving a 1 mega-byte file across the network would require an untuned load-adaptive routing around 16 seconds as opposed to 10 seconds by hop count. The wireless mesh networks will have to be awake for more than 60% longer with more nodes participating.

In other words, when there is a very wide space to maneuver around the mesh network, an improperly tuned load-aware routing metric would actually force far more nodes to participate

in forwarding packets, and would greatly send far more packets to the channel, with a lot longer packet arrival times than what the commonly used hop count metric would do. This would translate to a great deal of additional power usage for the network. For wireless sensor networks that are composed of nodes that depend only on batteries [23], this additional power usage is going to be a major problem.

C. Forward-delay Product (FDP)

To better quantify the energy efficiency and stability of a proposed routing metric or scheme, we introduce a figure of merit called forward-delay product (FDP). Mathematically, the forward-delay product relates to the amount of traffic that may be in transit across the network. Although this definition is similar to the bandwidth-delay product [22] when applied in wired networks, however, the forward-delay product is analogous to the energy-delay product as used in logic circuit design [24]. Since energy spent by the network is proportional to the amount of traffic it forwards and receives [25], this metric should come handy when comparing energy efficiency and stability of different routing schemes in wireless mesh networks. Equation (1) defines this value.

$$FDP = \frac{\text{input traffic} * \text{forwarding rate} * \text{packet delay}}{\text{received traffic}} \quad (1)$$

Figure 3 shows the average forward-delay product of CLM-based routing with respect to that of the hop count. FDP gives the amount of data that will be in transit in the network to move the same amount of input across the network. On the average, the forward-delay product of CLM is 283% more than that of the hop count-based routing. This means, to get across the same input traffic, proportionally CLM-based routing would require almost 3 times as much work or energy.

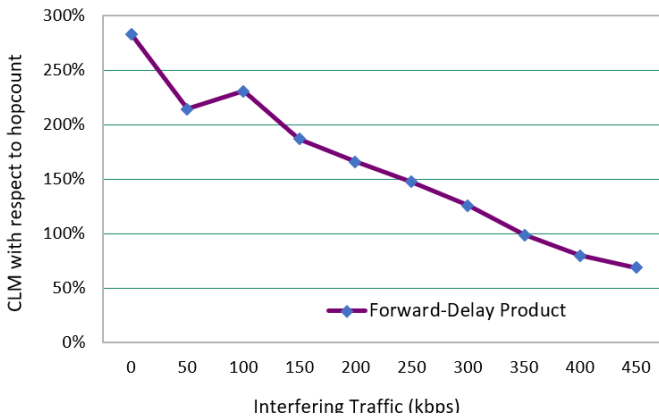


Figure 3: Performance comparison of CLM with respect to hop count based routing in terms of average forward-delay product

D. Security Issues

In a wireless mesh network that are composed of nodes with limited supply of power, like in wireless sensor networks [23], the instability of the routes could pose a weakness that may be exploited by rouge nodes. In case the wireless network is used as a backbone network where the clients are only connected at the edge nodes (Figure 4), a malicious client may pump heavy traffic from one end of the network towards the other end. Considering the 0-kbps interfering traffic scenario in Figure 2 where an untuned load-aware routing metric CLM spread 283% times traffic across the network. Proportionally, this amount of traffic requires 3 times as much energy as hop count based routing. This tendency forces more nodes to work than usual, eventually

draining the batteries of most network nodes, potentially bringing down the network.

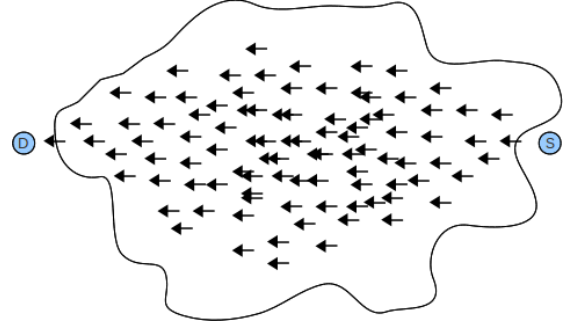


Figure 4: A node S sending traffic to node D

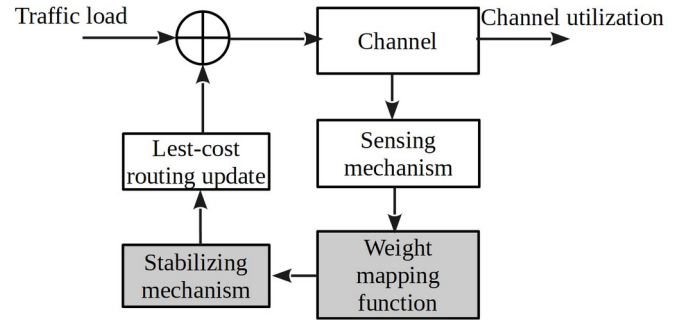


Figure 5: The feedback mapping system for load awareness

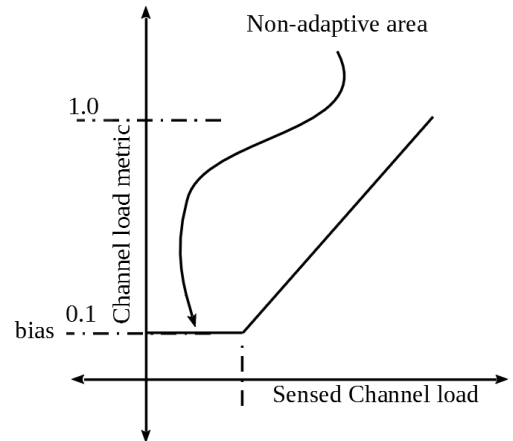


Figure 6: The weight mapping function

IV. FEEDBACK-AWARE MAPPING SYSTEM

In a previous work [21], CLM is defined as the fraction of time that the channel is sensed as busy (due to on-going transmission or interference) or is in-accessible (such as due to back-off and defer periods). To stabilize the routing adaptation due to load changes in the channel, the routing process is considered as analogous to a control system with a feedback control [26] (see Figure 5). This design integrates the mapping function block in Figure 5 to CLM's load-sensing technique (see Figure 6) with a mechanism that addresses non-convergence of the routing algorithm at light load scenarios. This is represented by the non-adaptive area in the weight mapping function which effectively serves as a bias [10]. A previous work used [27] used 0.1 for the bias, so is here.

To keep the control method simple, this design did not include changes in the routing algorithm and route update blocks, but rather focused on the channel load mapping function and on an added memory weighted averaging function that regulates further instability contributed by sudden traffic bursts. Figure 5 shows

this as the stabilizing mechanism block and employs an averaging approach similar to that used previously [13], [27].

E. Better Network Performance

Continuing with the simulation testbed described in Section III, we present the behavior and performance of the feedback mapping system called FARM. In these set of traffic scenarios a single source sends traffic towards the other end of the network. An interfering traffic is present at the center of the network, along the path of the main traffic (see Figure 1). The mesh network is widely open in terms of routing and propagating packets. In this kind of situation, a load-adaptive routing has the tendency to oscillate the worst and become unstable because of the availability of more lightly-loaded routes to choose from.

Figure 7, Figure 8, and Figure 9 summarize the performance comparison between FARM enhanced CLM (FARM-CLM), CLM, and hop count based routing, in terms of average received throughput, average end-to-end packet delay, and average forward-delay product respectively. The percentages at the y-axis tell the difference between the performances of two routing metric with respect to each other. For example, in Figure 7, the first (yellow) and second (red) lines tell the difference (in percent) of FARM-CLM average received throughput with-respect-to CLM and FARM-CLM average received throughput with-respect-to hop-count respectively. In all scenarios, FARM-CLM outperforms hop count and CLM-based routing in terms of received throughput; it outperforms hop count by 28% more on the average and 64% at best. It outperforms CLM by 58% more on the average 68% at best in average received throughput. The reason for these results is due to the fact that, first, it is able to converge and stabilize routes. And, second, FARM-CLM is able to move around the loaded center region, avoiding more packet losses due to collisions, hence increasing throughput.

Meanwhile, Figure 8 shows FARM-CLM has shorter average end-to-end packet delay than that of CLM-based routing, 22% at best and 13% shorter at the least. However, at lighter center traffic scenarios, 0 to 300 kbps, FARM-CLM had longer end-to-end packet delay than hop count based routing. These results can be explained by the fact that, FARM-CLM adapts the routes and directs them around the loaded center, taking longer route, hence longer average packet delay despite better received throughput; and secondly, hop count based routing encountered not enough center traffic to cause collisions and retransmissions that may cause longer packet delay than that incurred in FARM-CLM-based routing.

Nevertheless, at scenarios beyond 300 kbps center traffic, FARM-CLM average end-to-end packet delay either match that of hop-count or is better. In these scenarios, hop count continuously directs traffic on the shorter path through the center of the network, where its traffic collides with that of node 40 and 48, dropping and resending packets. This is the main reason why FARM-CLM, at these scenarios, has huge advantage in received throughput, 53-64% more (see Figure 7) over hop count.

In terms of energy efficiency, Figure 9 shows that FARM-CLM continuously improves on CLM, 53-63% less. Recall that the lower value of a forward-delay product correlates to better energy efficiency. However, with respect hop-count based routing, FARM-CLM advantage appears only at the heavier center traffic scenarios and may perform less desirably at the lightly-loaded situations.

F. In Summary

FARM-CLM is able to stabilize a load-adaptive routing metric, consequently improving on received throughput, end-to-end packet delay, and energy efficiency. In the presence of a loaded region along the way towards a destination, FARM-CLM-based routing also performs better than the more commonly used

hop count routing metric. These performance improvements are due to the fact that it can direct traffic around the loaded region. However, if the load is not heavy enough and there is space to maneuver, FARM-CLM-based routing achieves better throughput at the expense of more delay and less energy efficiency. The reasons for the later behavior are, first, is that the low traffic level of the busy region does not generate enough collisions and retransmissions for hop-count based routing to cause packet delay longer than the packet delay incurred using FARM-CLM and larger forward-delay product. And, secondly, despite the achieved level of stability of FARM-CLM-based routing oscillates especially at light load scenarios. For this reason, part of an interesting future work includes a deeper investigation of the adjustable parameters of the control method for FARM-CLM and an exploration of other control methods like adaptive control [28] and fuzzy logic [29].

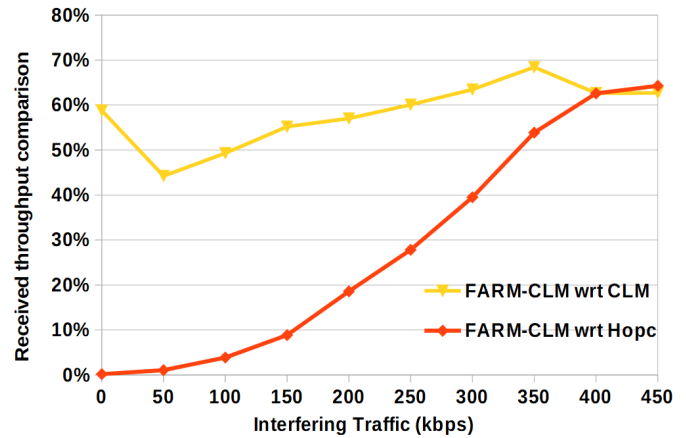


Figure 7: Average received throughput comparison

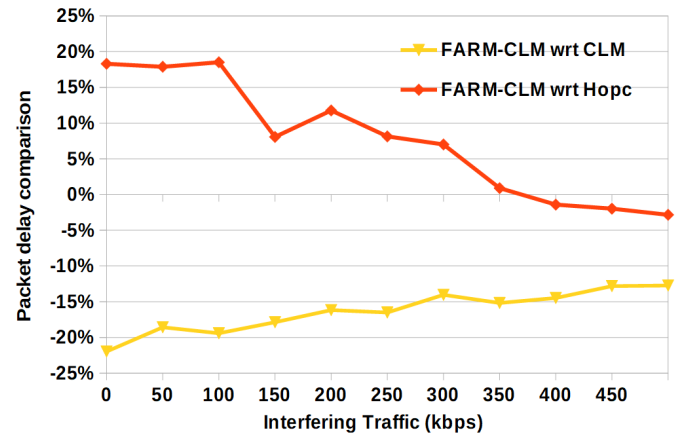


Figure 8: Average end-to-end packet delay comparison

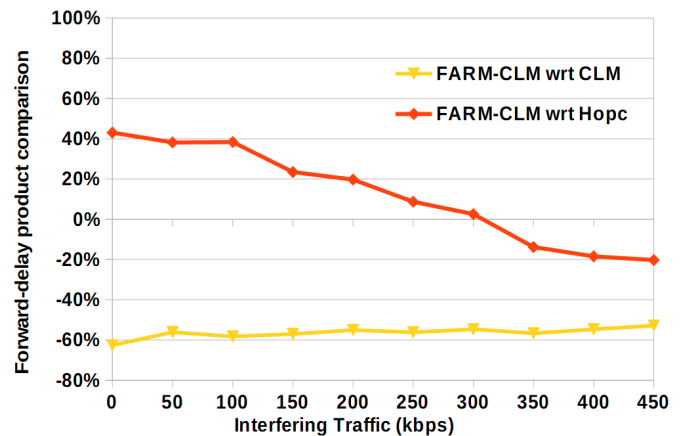


Figure 9: Average forward-delay product comparison

V. CONCLUSIONS AND FUTURE WORK

Caution must be taken replacing commonly-used hop count routing metrics [15] with a load-adaptive ones. Adaptiveness would not necessarily improve network performance because of feedback effects that cause route instability. In WMNs, this instability has been described primarily as oscillations [6], [12], [14]. We show that performance degradations are more due to route convergence issues. These issues in turn bring about energy efficiency and security issues. To the best of our knowledge, these results have not yet been reported in the literature and should prove helpful to other researchers.

Accordingly, this work presented a **simulation test bed** and a figure of merit called **forward-delay product** for studying the load-adaptive behavior and revealing the (in)effectiveness respectively of a proposed load-aware routing metric. The test bed has enough space for load-adaptive routing to maneuver around in the absence and presence of congestion in the network, that could expose its instability. On the other hand, the forward-delay product is a metric that should come handy when comparing energy efficiency and stability of different routing schemes in wireless mesh networks. Finally, we also present a **feedback aware mapping (FARM) system** that handles the above mentioned routing instabilities in a manner analogous to a control system with feedback control. FARM-CLM is able to stabilize a load-adaptive routing metric, consequently improving on received throughput, end-to-end packet delay, and energy efficiency.

In the end, our system must be fully realized through a working implementations rather than theoretical simulation that we hope to address in the future.

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