Effective Link Operation Duration: a New Routing Metric for Mobile Ad Hoc Networks

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***Abstract*—The dynamic topology of mobile ad hoc networks (MANETs) is caused by node mobility and fading of the wireless link. Link reliability is often measured by the estimated lifetime and the stability of a link. In this paper we propose that the stability of a link can be represented by the time duration in which the two nodes at each end of a link are within each other's transmission range and the fading is above an acceptable threshold. A novel routing metric, called effective link operation duration (ELOD), is proposed and implemented into AODV (AODV-ELOD). Simulation results show that proposed AODV-ELOD outperforms both AODV and the Flow Oriented Routing Protocol (FORP).**

***Index Terms*—mobile ad hoc network, MANET, routing metric, link lifetime.**

I. Introduction

A mobile ad hoc network (MANET) is characterized by a dynamic topology which is introduced by node mobility as well as by channel fading. Shortest hopcount routing protocols, such as ad-hoc on-demand distance vector routing (AODV) [1], choose routes which may not last very long. Thus, we propose to utilize a metric characterizing link stability to choose the most stable links in the network [2], [3], [4]. Many routing protocols proposing to find more stable routes can be found in the literature. Route lifetime Assessment Based Routing (RABR) [5] predicts the link lifetime using the measured value of average change in received signal strength over the last few samples. The Flow Oriented Routing Protocol (FORP) [6] makes use of node movement to predict the link expiration time, and discover routes. The authors in [4] propose a probabilistic link availability model, where link availability is defined as the probability that there is an active link between two mobile nodes at time $T + t$ given that this link is available at time T and, in [7], an improved model using a path reliability metric is illustrated. Two link stability metrics are proposed to categorize stable links in [8] based on empirical distributions of link duration and residual link lifetime.

While most of the existing schemes mainly focus on the impact of node mobility on link reliability, they have ignored the channel fading. Multipath fading is one of the primary factors which affects the throughput of mobile ad-hoc networks. The envelope of the signal in a time-varying fading channel experiences deep fades when multipath signals are combined destructively [9], which makes causes high bit error rates and packet losses. When a link suffers from a fade:

1) if the fade is shallow, or lasts only for a short interval, it can be combated by physical layer (PHY) techniques, such as error control coding, or by adopting retransmission schemes in the medium access control (MAC) protocol in the data link layer, allowing link connection to continue;
2) if the fade is deep and lasts for a long time, which might incur a number of continuous packet losses, the link will be disconnected.

However, in both cases, the channel fading incurs extra network overhead in the PHY, MAC, or network layer. We propose to measure the stability of a link by the duration for which the nodes at the edges of the link are within each other's transmission range with no fading. We call this new metric *effective link operation duration* (ELOD).

In this paper, ELOD is introduced as a new routing metric to select links in terms of reliability in a mobile ad hoc network. The prediction scheme combines node mobility with channel fading. First, it makes use of node mobility to predict the link lifetime. Then it combines the link lifetime with the fading channel statistics to obtain the ELOD. The ELOD is incorporated into AODV (AODV-ELOD), to improve the network performance. AODV-EOLD is shown to outperform both ordinary AODV and FORP.

The layout of this paper is as follows. In Section II we define the routing metric, ELOD. In Section III we describe the channel model and the calculation of ELOD. The improved routing protocol is presented in Section IV. Simulation results are presented in Section V and in Section VI we draw our conclusions.

II. Effective Link Operation Duration

Packet propagation in wireless networks suffers from the long-term (large-scale) fading and short-term (small-scale) fading. In large-scale fading, the average received signal strength attenuates with the propagation distance. Small-scale fading is introduced by multipath and the Doppler effect. In a flat fading channel, the instantaneous received signal amplitude has a Rayleigh distribution [10]. In Fig. 1 we give an example of the movements of, and the relative distance between, two nodes A and B. In Fig. 2 the fluctuations of the received signal power for node A from node B is plotted, where both large-scale fading and small-scale fading are included.

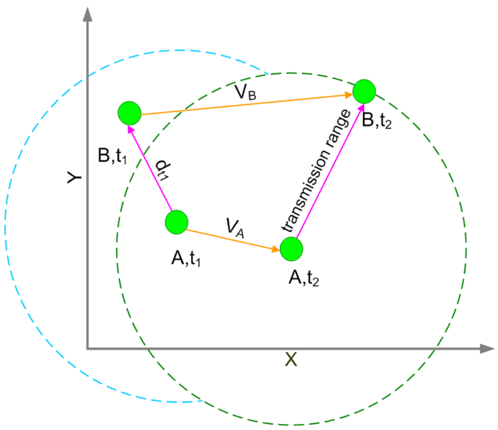

Fig. 1. Example of movement, V_A and V_B, and the relative distances between nodes A and node B at times t_1 and t_2.

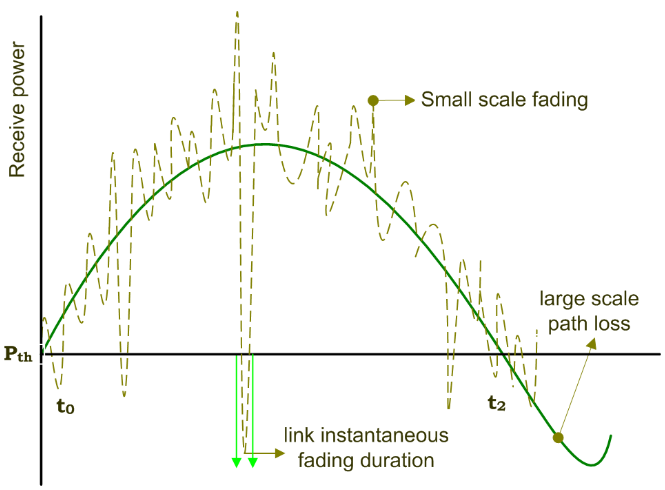

Fig. 2. The fluctuations of the received signal power for node A from node B, where both large-scale path loss and small-scale fading are included.

Any measure of link reliability should include an indication of how stable the link is in terms of longevity. When channel fading is taken into consideration, we propose that the stability of a link should be represented by the time for which the link is up, which is not the duration in which the nodes are within each other's transmission range, but the one in which the nodes are within each other's transmission range with no fading. The former is defined as link lifetime, T_f, and the latter as effective link operation duration (ELOD), D_ℓ. The relationship between link lifetime and ELOD is

$$D_\ell = T_f \Pr\{\text{link } \ell \text{ in connection during } T_f\}. \quad (1)$$

The ELOD is actually the total time duration within the link lifetime in which the received signal power is above a certain predefined threshold. The introduction of ELOD has particular benefits for mobile ad hoc networks. For example, a link composed of nodes with long pause times that are located at the edge of each other's transmission range, will have a relatively long lifetime with high bit error rate. When incorporating channel fading, the ELOD for such a link might not be very high, reflecting the true effectiveness of the link.

III. Calculation the ELOD

A. Channel Model of the Mobile ad hoc Network

In this paper we assume that the channel for each link is subject to flat fading. The wireless channel model includes the effects of small-scale fading and large-scale path-loss. We assume that the transmit power is fixed and the same for each node. For a transmission over a distance d, in the presence of Rayleigh fading, the received signal power P_r is exponentially distributed with mean $P_t d^{-\alpha}$ [11], where P_t is proportional to the transmit power and α is the propagation loss coefficient, typically between 2 and 4. The probability Θ that the received signal power above a specified threshold P_{th} is

$$\Theta = \Pr\{P_r \geq P_{\text{th}}\} = e^{-\frac{P_{\text{th}}}{P_t d^{-\alpha}}}. \quad (2)$$

B. Effective Link Operation Duration Estimation

In this section, we describe how to predict the link operation duration (ELOD) for a link in a mobile ad hoc network. We assume all the nodes in the network are equipped with a Global Positioning System (GPS) to enable them to determine their current positions and velocities. Assume all the nodes in the network have equal transmission range R, and the movement of the nodes is according to a random waypoint model [12], where each node travels with a fixed speed for a given period of time. For the two nodes A and B in Fig. 1, with respect to a stationary Cartesian coordinate system, let (x_i, y_i) be the x-y position for mobile node i, and $(v_{i,x}, v_{i,y})$ be its speed components. We can predict the link lifetime T_f from [6]:

$$T_f = \frac{-(d_x v_x + d_y v_y) + \sqrt{R^2(v_x^2 + v_y^2) - (d_y v_x - d_x v_y)^2}}{v_x^2 + v_y^2} \quad (3)$$

where $d_x = x_B - x_A, d_y = y_B - y_A, v_x = v_{B,x} - v_{A,x}$, and $v_y = v_{B,y} - v_{A,y}$.

Using the statistics of the channel fading from (2), which is the probability that a link is not in a fade, we can estimate the link operation duration D_ℓ. However, because of the movement of the nodes, the relative distance between them is time-varying, which makes Θ vary with node movement. To account for this random topology, we replace d in (2) with a random variable Z, denoting the distance between the transmitter and the receiver. Therefore, the expected value of the probability $\mathrm{E}[\Theta]$ can be written as

$$\mathrm{E}[\Theta] = \int_{\mathrm{d_{min}}}^{R} e^{-\frac{P_{\text{th}}}{P_t Z^{-\alpha}}} f_Z(z) dZ \quad (4)$$

where $\mathrm{d_{min}}$ is the minimum distance between the two nodes at the ends of a link during the prediction period, and $f_Z\{z\}$ is the probability density function (pdf) of the random variable Z. Because we assume that the speed of a node is constant during the prediction period, the distance between two nodes should have a uniform distribution. Then, we can determine $f_Z\{z\}$ for the following distinct cases:

Case 1if the relative distance between nodes A and B stays fixed during their movement, the average Θ for the link during the prediction period is

$$\mathrm{E}[\Theta] = e^{-\frac{P_{\mathrm{th}}}{P_t d_{t1}^{-\alpha}}} \tag{5}$$

with $d_{t1} = \sqrt{d_x^2 + d_y^2}$;

Case 2if the two nodes only move away from each other during the prediction period, the pdf of Z is

$$f_Z\{z\} = \begin{cases} 0, & z < d_{t1}; \\ \frac{1}{R-d_{t1}}, & d_{t1} \le z \le R; \\ 0, & z > R. \end{cases} \tag{6}$$

The average Θ for the link in connection is

$$\mathrm{E}[\Theta] = \int_{\mathrm{d_{t1}}}^{R} \frac{1}{R - d_{t1}} e^{-\frac{P_{\mathrm{th}}}{P_t z^{-\alpha}}} dz. \tag{7}$$

For example, when $\alpha = 2$,

$$\mathrm{E}[\Theta] = \frac{\sqrt{\pi}}{2\rho(R - d_{t1})} \left[\Phi(\rho R) - \Phi(\rho d_{t1})\right] \tag{8}$$

where $\rho = \sqrt{\frac{P_{\mathrm{th}}}{P_t}}$, and $\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$;

Case 3if the two nodes first move toward each other, then apart some time later, the pdf of Z is

$$f_Z\{z\} = \begin{cases} \frac{2}{d_{t1}+R}, & z < d_{t1}; \\ \frac{1}{d_{t1}+R}, & d_{t1} \le z \le R; \\ 0, & z > R. \end{cases} \tag{9}$$

The average Θ for the link in connection is

$$\begin{aligned} \mathrm{E}[\Theta] &= \int_0^{\mathrm{d_{t1}}} \frac{2}{d_{t1} + R} e^{-\frac{P_{\mathrm{th}}}{P_t Z^{-\alpha}}} dZ \\ &+ \int_{\mathrm{d_{t1}}}^{R} \frac{1}{d_{t1} + R} e^{-\frac{P_{\mathrm{th}}}{P_t Z^{-\alpha}}} dZ. \end{aligned} \tag{10}$$

For $\alpha = 2$,

$$\begin{aligned} \mathrm{E}[\Theta] &= \frac{\sqrt{\pi}}{\rho(d_{t1} + R)} \Phi(\rho d_{t1}) \\ &+ \frac{\sqrt{\pi}}{2\rho(d_{t1} + R)} \left(\Phi(\rho R) - \Phi(\rho d_{t1})\right). \end{aligned} \tag{11}$$

Then, for these three cases, we can estimate the ELOD for a link ℓ as

$$D_\ell = T_f \mathrm{E}[\Theta]. \tag{12}$$

IV. Routing Protocol with ELOD

In this section, we describe how to incorporate the ELOD into the routing protocol. We implement ELOD in AODV and call it AODV-ELOD. We define D_r, the ELOD for a path r, as the minimum ELOD over all links in the path, such that $D_r = \min_{\ell \in r}[D_\ell]$. Using ELOD as the routing metric, we will obtain paths composed of links with longer durations, free of fading. However, such a path might have many more hops than the shortest one. When packet relaying involves more hops, since the radio channel is shared among neighbouring nodes in the network, it will increase medium access contention, interference, congestion, and packet collisions. Therefore, path length should also be considered when selecting a suitable path based on stability.

A. Routing Metric

First, we illustrate the impact of path length on network performance. Assume that there are N nodes in an ad hoc network which are independently and uniformly distributed in a rectangular area $\mathbb{L}^2$ with length L on each edge. The node spatial intensity is $\lambda = N/L^2$. For a node with transmission range R, the average number of neighbours is $n = \lambda \pi R^2$. Assume C is the number of connections in the network. Tthe expected distance between source and destination for each connection is $\frac{L}{3}(\sqrt{2} + \ln(1 + \sqrt{2}))$ [13]. The expected number of hops $\bar{H}$ required to deliver a packet can be approximated as

$$\bar{H} = \frac{(\sqrt{2} + \ln(1 + \sqrt{2}))L}{3R}. \tag{13}$$

Thus, the maximum number of nodes in the network which might be involved in packet deliveries is

$$N_a = \begin{cases} \bar{H}C, & \bar{H}C < N; \\ N, & \bar{H}C \ge N. \end{cases} \tag{14}$$

Then, the probability that a node has packets to transmit is N_a/N. In networks using the IEEE 802.11 distributed coordination function (DCF), nodes within each other's transmission ranges cannot transmit at the same time. When operating under heavy traffic conditions (every node always has packets to transmit), 802.11 DCF provides long term per packet fairness in single-hop networks [14]. Thus each node in the shared radio has a probability of $1/n$ of occupying the channel. Combining the probability that a node has packets to transmit, the average node transmission probability is $N_a/(nN)$. For a transmitting node on an active path, the probability that it can occupy the channel, or the probability that the channel won't be occupied by any of the $n - 1$ neighbours, is

$$q = 1 - \frac{N_a(n-1)}{nN}. \tag{15}$$

For transmission over one-hop, q is the average achievable throughput due to channel access contention. Assume a path is composed of h hops. The average achievable path throughput Ψ is

$$\Psi = D_r q^h = D_r \left(1 - \frac{N_a(n-1)}{nN}\right)^h. \tag{16}$$

The throughput, Ψ, combines the impacts of ELOD and path length. In AODV-ELOD, we use Ψ as the routing metric to select stable paths with higher throughput.

B. The Proposed Routing Protocol AODV-ELOD

We implement the routing metric, Ψ, into routing protocol AODV-ELOD. The routing path establishment and maintenance procedure of AODV-ELOD is similar to that of AODV.

During the route discovery stage, before propagating the RREQ packet to its neighbours, a node will insert its current location and speed in the RREQ header for the receivers to calculate the Ψ of the link. The intermediate nodes and the destination can then determine the Ψ for the route by using the information in the RREQ packets. A node which receives a RREQ will forward it further, if the RREQ has a higher sequence number than any of the previously received RREQs for an advertised source-destination pair, or if the received RREQ has the same sequence number as previously received ones for the same destination, but with a higher Ψ. After the destination receives a RREQ, it delays for a short while, in order to obtain as many as possible, then selects the path with the highest Ψ and feeds a RREP back to the source.

V. SIMULATIONS

The performance of the proposed AODV-ELOD is compared with that of AODV, and FORP using the network simulator ns-2.30 [15] with Rayleigh fading channel extension [16], where the handoff scheme in FORP is omitted to focus on the comparison of the routing metrics. Physical layer parameters of the Lucent WaveLAN wireless network card [15] is adopted in the simulations. The radio transmission range is 250m. The Random waypoint [12] model is used for node mobility. The medium access control (MAC) protocol is IEEE 802.11 DCF. All mobile nodes have the same channel bandwidth of 2 Mb/s. Scenarios for the simulation were configured with an 80-node 10-connection network in a 1500m $\times$ 1500m terrain, where the nodes are uniformly distributed in the network and randomly move with maximum speed. Each simulation was run for 300s.

A. *Varying Node Mobility*

First, we compare the performance of the routing protocols in time varying mobility multihop networks. The node maximum speed is increased from 2 m/s to 40 m/s to raise node mobility. Constant Bit Rate (CBR) sources are used at a rate of 4 packets per second with a size of 512 bytes and transmit to randomly chosen destinations.

The simulation results for network throughput, normalized routing control overhead, average end-to-end delay and route discovery frequency are shown in Fig. 3, Fig. 4, Fig. 5, and Fig. 6, respectively. From the figures, it can be seen that while the network performance for all three routing protocols decreased with the increased node mobility, the AODV-ELOD always outperforms the other two routing protocols. FORP has the worst performance, which is because FORP chooses paths composed of links with longer lifetimes, but the paths might include more hops to reach the destination. The increased hops raises the network interference, contention, and packet collisions. Under a high mobility environment, long paths are fragile because any movement of a node on the path might cause the path to fail. AODV uses shortest hop-count metric, which makes it tend to select links composed of nodes that are located at the edge of each other's transmission range. Compared with the other two routing protocols, AODV-ELOD takes account of both link reliability and hop-count.

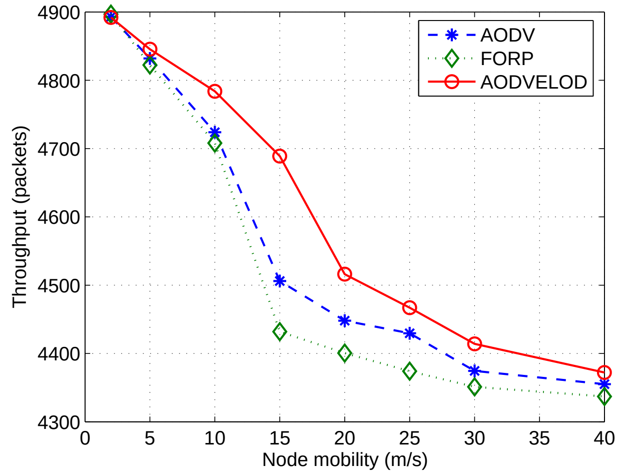

Fig. 3. Throughput comparison under different node mobility.

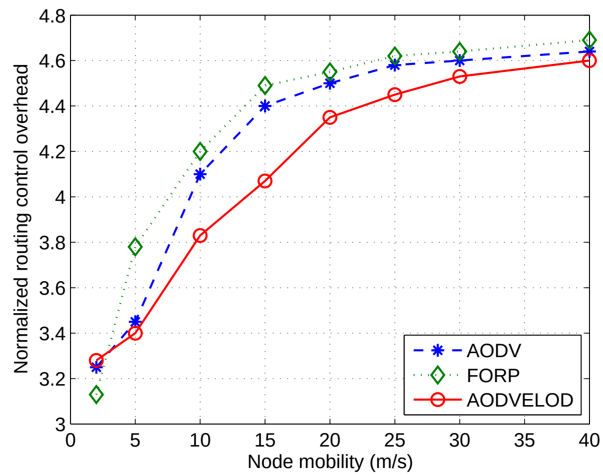

Fig. 4. Normalized routing control overhead comparison under different node mobility.

Moreover, the criterion for link reliability in AODV-ELOD incorporates node movement with channel fading statistics. Thus, AODV-ELOD can select paths with shorter length and more stable links, improving network performance. However, AODV-ELOD assumes the nodes do not move during the interval in which the channel statistics are predicted, which might introduce some prediction errors and reduce the network performance, especially when the node movement is high (over 25 m/s).

B. *Varying Traffic Load*

Secondly, we fixed the node maximum speed at v =5 m/s while varying the packet rate at each source from 1 to 30 packets/second, to evaluate the performance of the routing protocols with increasing network traffic load. Fig. 7 illustrates the network packet delivery ratio (PDR), while Fig. 8 shows the average end-to-end delay for the routing protocols with varying packet rate. For all of the routing protocols, perfor-

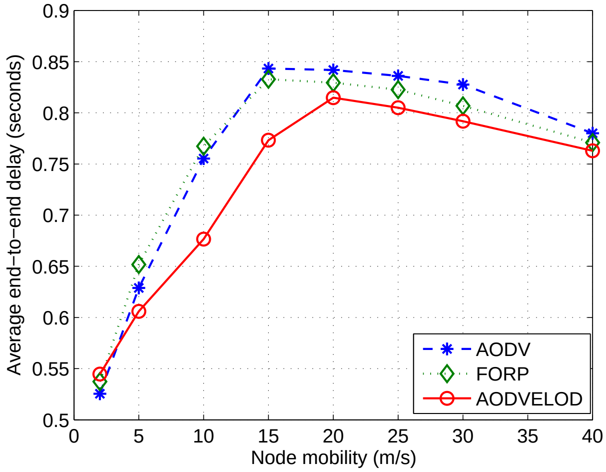

Fig. 5. Average end-to-end delay comparison under different node mobility.

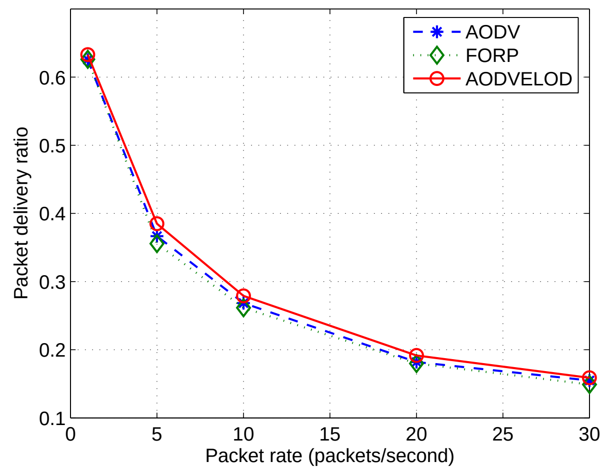

Fig. 7. Packet delivery ratio comparison under varying traffic load.

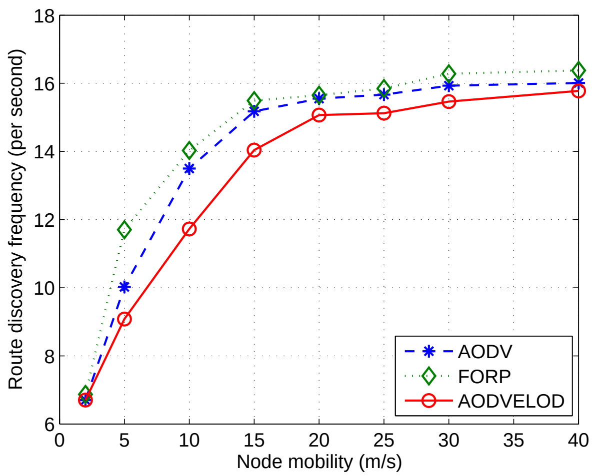

Fig. 6. Average route discovery frequency comparison under different node mobility.

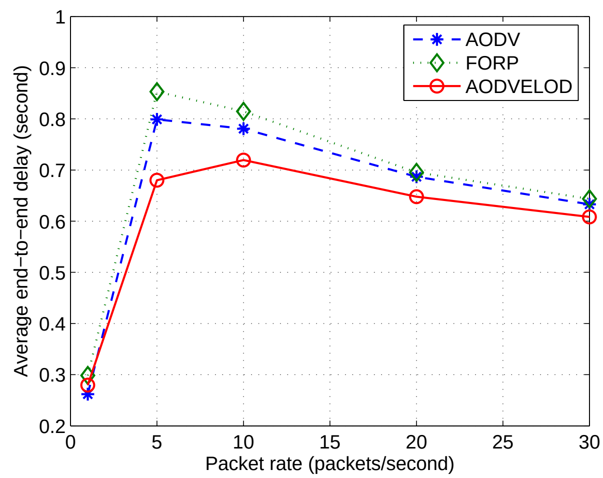

Fig. 8. Average end-to-end delay comparison under varying traffic load.

mance decreases with increasing traffic load. The performance degradation is due to the increased interference and congestion when the network traffic load is increased. We can see that AODV-ELOD has better performance in terms of PDR and average end-to-end delay than AODV and FORP. This is due to the channel-aware metric in AODV-ELOD, which makes the routing protocol choose long-lasting, high throughput links, to reduce network failure, increasing network throughput and decreasing end-to-end delay.

VI. Conclusion

Mobile ad hoc networks are characterized by dynamic topologies, introduced by node mobility and channel fading. The stability of links should be represented by node movement as well as channel fading statistics. In this paper, we propose a new routing metric, effective link operation duration (ELOD), which is the time during which which the nodes are within each other's transmission range with no fading. We implement the new routing metric in AODV, taking into account path length, interference, and medium access contention. Simulation results show that AODV-ELOD achieves better performance than AODV and FORP over a range of network performance measures.

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