DIAR: A Dynamic Interference Aware Routing Protocol for IEEE 802.11-based Mobile Ad Hoc Networks

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Abstract. A fundamental issue impacting the performance of mobile ad hoc networks is the wireless interference among neighboring nodes. In this paper, we derive an interference aware metric NAVC based on the information collected from the IEEE 802.11 Medium Access Control (MAC) layer. We then propose a novel Dynamic Interference Aware Routing protocol (DIAR) building on NAVC and AODV [3]. Both mathematical analysis and experimental study indicate that NAVC can effectively predict available bandwidth and delay. Simulation results indicate that the overall system performance can be improved by DIAR compared to AODV.

1 Introduction

A wireless mobile ad hoc network (MANET) is an autonomous system of mobile nodes that wish to communicate with each other. Usually, the mobile nodes are powered by battery. The communications among neighboring nodes suffer from limited bandwidth, co-channel and cross-channel interferences, unidirectional links, etc. Therefore, a MANET is featured by infrastructurelessness, strict resource constraints (such as power supply, CPU processing capability, storage budget, etc.), nodes mobility, multihop communications, just name a few. As a result of these characteristics, designing a high performance routing protocol for MANET is a very challenging problem.

Many recent routing protocols [1–4] choose routes with a minimum hop-count, ignoring the possibility that a longer path might offer higher throughput. Further, in these protocols, an arbitrary path among those with the same hop-count may be selected, regardless of their large differences in performance. These protocols have been shown in simulation to work very well on small to medium networks [5]. However, they only achieve a small portion of the network capacity, as reported by Das *et al.* [6]. For example, in one of their network scenarios

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containing 100 nodes with 2Mbps links, the throughput of each node is in the order of a few kilobits per second.

The pure hop-count metric is misleading for a long time because it may choose routes that have significantly less capacity than the best one in the network [7], especially for dense networks in which many paths with the same minimum hop-count may exist. Therefore, there still exist significant challenges in finding and choosing better routes in MANET.

Recently, several routing protocols [8, 9] with new metrics have been proposed aiming at improving performance parameters such as power consumption, throughput, and the entire network life time. In PARO [8], a power-efficient route can be constructed via a cost function based on the low energy-consuming route between a pair of nodes. In [9], a high throughput path metric called Expected Transmission Count (ETX), which is obtained from link loss characteristics between the two directions of each link and the interference among the successive links of a path, has been developed by Douglas *et al.* ETX-driven routing protocols can substantially improve the system performance, though in a scenario involving a mobile sender, the minimum hop-count routing performs considerably better because the metric does not react sufficiently quickly [10].

However, none of these state-of-the-art routing protocols touches the key to the performance improvement of MANET. As pointed out by Gupta and Kumar [11], the fundamental reason leading to the degradation of the performance as the number of nodes increases is the fact that each node has to share the radio channel with its neighbors. Subsequently, finding practical wireless interference-aware metric for network layer to make routing decisions becomes critical. As reported by [12], there still exists an opportunity for achieving throughput gains by employing an interference-aware routing protocol.

To the best of our knowledge, [13] is the only work that intends to utilize the interference information obtained from the MAC layer to improve routing efficiency. However, the interference metric in this work is not the core part leading to the routing decisions but a small portion of the proposed metric. Further, this work only considers low mobility nodes such as stationary objects or pedestrians with low speed.

To maximize the system performance, we propose DIAR, a novel Dynamic Interference-Aware Routing protocol that extends the AODV [3] with an interference aware metric, which replaces the hop-count metric in AODV. The main contributions of this paper are the followings: (i) We propose a novel interference-aware metric named Network Allocation Vector Count (NAVC) for MANET. (ii) We derive a function to predicate the possible delay and the available bandwidth based upon NAVC. (iii) The design of DIAR with the interference-aware metric NAVC is described in detail. (iv) We show that in scenarios with moderately high traffic load, our DIAR outperforms the traditional AODV though the former uses longer paths.

The remaining of this paper is organized as follows. Section 2 details the derivation of our interference aware metric. Our dynamic interference aware routing protocol is proposed in Section 3. Simulation settings and results are reported in Sections 4 and 5, respectively. We conclude this paper with a future research discussion in Section 6.

2 Interference Analysis and Metric

In this paper, we adopt the point-to-point coding model of [11] in which at any given time, one receiver only decodes messages from one sender, considering all other simultaneous transmissions purely as noise. Similarly, at any given time, one sender transmits information only to one receiver. According to this model, each node will interfere with its neighbors when sending packets, while encounter interference from its neighborhood when they are transmitting. Any node-to-node transmission adds to the level of interference experienced by other nodes.

2.1 Mathematical Preliminary

Consider the following stochastic integral equation:

$$x\left(t\right) = x\left(0\right) + \int\limits_0^t f\left(x\left(\tau\right), \tau\right) d\tau + \int\limits_0^t g\left(x\left(\tau\right), \tau\right) dN_\tau. \tag{1}$$

Definition: $x\left(\cdot\right)$ is a solution to Eq. (1) in the Itô sense if on an interval where N is a constant and x satisfies $\dot{x} = f\left(x, t\right)$, and if when N jumps at t_1, x changes according to Eq. (2):

$$\mathop{lim}_{t \to t_1^+} x\left(t\right) = g\left(\mathop{lim}_{t \to t_1^-} x\left(t\right), t_1\right) + \mathop{lim}_{t \to t_1^-} x\left(t\right). \tag{2}$$

Rewrite Eq.(1) as

$$dx(t) = f(x,t)dt + g(x)dN. \tag{3}$$

Eq. (3) is called a *Poisson* counter driven stochastic differential equation (SDE) [14] and [15].

2.2 Interference Analysis

To analyze the interference, we must first study the channel contending mechanism in IEEE 802.11 protocol. The primary MAC technique of IEEE 802.11 is called *distributed coordination function* (DCF). Specifically, DCF uses a random back-off procedure to resolve medium contention conflicts and a virtual carrier-sense mechanism that exchanges RTS/CTS frames to announce the impending use of the medium. Once a node hears other nodes transmission, its Network Allocation Vector (NAV) will be set to busy state and this node has to keep silence for a duration equal to the value in the *Duration-ID* field of the RTS header. The higher the traffic rate, the larger the accumulated NAV duration value, and vice versa.

The NAV in the 802.11 MAC protocol can be a good indicator of the neighboring traffic. Therefore, according to the definition given by Eq. (3), the channel situation (free or busy) sensed by one node can be regulated via Eq. (4):

$$dx\left(t\right)=\left(1-x\left(t\right)\right)dN_1-x\left(t\right)dN_2\quad x\left(0\right)\in\left\{0,1\right\} \tag{4}$$

Eq. (4) models the on-off Markov modulated sources, which refer to the neighboring traffic. Compared to Eq. (3), Eq. (4) does not contain the term $f(x,t)$, but contains two *Poisson* counters N_1 and N_2. Subsequently, $x(t)$ remains unchanged in an interval where N_1 and N_2 are constant. When N_1 or N_2 does jump, apply Eq. (2) and $x(t)$ will flip between 0 (channel free) and 1 (channel busy). Assume λ and μ are the rates of $\mathrm{N}_1$and N_2, respectively. Then, we can easily get the expectation of $x(t)$ in steady state, denoted by εx

$$\varepsilon x=\frac{\lambda}{\lambda+\mu} \tag{5}$$

From Eq. (5), we can conclude that the interference (channel busy) encountered by one node from its neighborhood is determined by λ and μ .

For simplicity, we assume that at each node the packet processing rate C is a constant and the buffer size is reasonably large [16]. Thus, the increment of the queue length at one node can be described by Eq. (6):

$$dv\left(t\right)=-cI_v dt+hx\left(t\right)dt \tag{6}$$

where $hx(t)$ represents the rate of packets inserted into the queue caused by the interference. Here, the notation I_v is the indicator function for $v>0$, while v is the queue length.

Now, consider the expectation of $dv(t)$, denoted by $d\varepsilon v$.

$$d\varepsilon v=-c\varepsilon I_v dt+\varepsilon\left[hx\right]dt \tag{7}$$

Dividing both sides of Eq. (7) by dt, we get

$$\frac{d}{dt}\varepsilon v=-c\varepsilon I_v+\varepsilon\left[hx\right] \tag{8}$$

Based on [15], we can deduce Eq. (9) and Eq. (10) based on the Itô formula, the Chain Rule, Eq. (5) and Eq. (8):

$$\frac{d}{dt}\varepsilon v^2=-2c\varepsilon v+2h\varepsilon xv \tag{9}$$

$$\frac{d}{dt}\varepsilon vx=\varepsilon\left(1-x\right)v\lambda-\varepsilon xv\mu-c\varepsilon x+h\varepsilon I_v x \tag{10}$$

It's very important to observe that $\varepsilon\ I_v x=\varepsilon x$ because v is positive whenever x is positive. Through Eqs. (8), (9) and (10), we get Eq. (11) and Eq. (12)

$$\varepsilon v = \left(c - h \frac{\lambda}{\lambda + \mu} \right)^{-1} \frac{h - c}{\lambda + \mu} \varepsilon[hx] \tag{11}$$

$$\varepsilon v^2 = 2 \left(c - h \frac{\lambda}{\lambda + \mu} \right)^{-1} \frac{h - c}{\lambda + \mu} c \varepsilon v \tag{12}$$

Remark: $h\lambda/(\lambda + \mu) > c$ always holds under normal situation, i.e., the average packet arrival rate ought to be lower than the node's packet processing rate. Otherwise the whole system can not work properly.

$1/(\lambda + \mu)$ represents the interference situation caused by neighboring nodes. From Eq. (11) and Eq. (12), we observe that the queue length monotonously increases when $1/(\lambda + \mu)$ increases and $h\lambda/(\lambda + \mu)$ keeps constant. Furthermore, it can be proved that a queue accumulating many packets may cause the Tandem Queue effect at the downstream nodes in a path [15].

2.3 Metric

We observe that the NAV in the 802.11 MAC protocol is a good indicator of surrounding traffic because it is set by the neighboring nodes' carriers. To measure the network interference condition parameter $1/(\lambda + \mu)$, we define the NAVC as follows:

$$NAVC = \frac{The\ total\ time\ that\ the\ NAV\ is\ set}{Observation\ period} \tag{13}$$

We notice that NAVC has the following features based on our extensive simulation study:

- NAVC is insensitive to the number of users and the traffic pattern.
- If NAVC $> 65\%$, system may overflow.
- If NAVC $< 20\%$, the delay is usually negligible. The relationship between the average delay and the NAVC is plotted in Fig. 1(a).
- With average packet size, we can easily estimate the residual bandwidth by using the NAVC. The relationship between the residual bandwidth and the NAVC is plotted in Fig. 1(b).

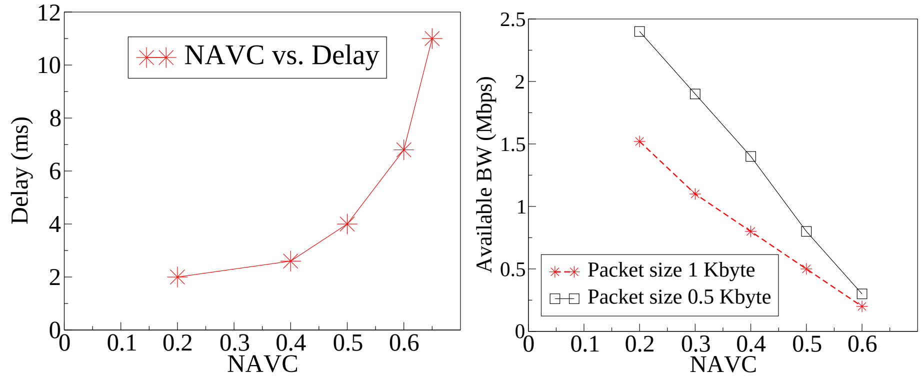
Therefore, as long as the NAV value can be sensed from the MAC layer, we can estimate the delay characteristics. If the average packet length is available, we can also estimate the residual bandwidth easily. We can approximate the delay and the available bandwidth with the following equations:

$$Delay(x) = \begin{cases} 2 \quad ms, & 0 \le x \le 0.2 \\ 2.0e^{7.9\ x - 0.2^2} ms, & 0.2 < x \le 0.65 \end{cases} \tag{14}$$

$$BW\,(L, x) = (0.0024L + 0.9) - (0.0036L + 1.4)\,x \tag{15}$$

where L is the average packet length and x refers to the NAVC value. For the detailed derivation of equations (14) and (15), we refer the readers to our previous paper [17].

Now we have introduced our interference aware metric NAVC. In the next, we will show how NAVC can be applied to make routing decisions.



(a) Average delay.

(b) Available Bandwidth.

Fig. 1. Network performance vs. NAVC.

3 The DIAR Scheme

As an interference aware metric, NAVC can be applied to any routing protocol proposed for 802.11-based networks. In this paper, we choose to build our dynamic interference aware routing protocol, i.e. the DIAR, by extending AODV with NAVC. AODV has been well-studied by the wireless ad hoc network society. It is a *reactive* routing protocol proposed for wireless ad hoc networks.

As an extension to AODV, DIAR is also an on-demand algorithm, building routes via a route request and route reply query cycle with the interference aware metric NAVC. The key idea of DIAR is to avoid selecting a route which has nodes that are severely interfered by their neighborhood such that the energy and delay caused by contention are minimized. In DIAR, each node computes its NAVC by periodically collecting the NAV values from its MAC layer. The operations of DIAR is sketched below.

Step 1: Route Request

When a source node desires a route to a destination for which it does not already have a path, it broadcasts a *route request* (RREQ) packet across the network. There are two extra fields namely *heavy_node_number* and *nav_sum* in the RREQ message compared to the AODV RREQ message. After receiving the RREQ packet, a node other than the destination has three options before continue broadcasting this message.

- If its NAVC is larger than 65%, increase the value of *heavy_node_number* by one and the value of *nav_sum* by the square of its NAVC.
- If its NAVC is somewhere between 20% and 65%, increase the value of *nav_sum* by the square of its NAVC only.
- In other cases, make no modification to these two fields.

Step 2: Route Reply

When the destination node receives any non-duplicated and valid RREQ message, it will send the *route reply* (RREP) message immediately. If an intermediate node already has a valid route to the destination, it can generate the RREP too.

Step 3: Route Update and maintenance

When any of the following conditions is satisfied, the route update process will be activated at the source, the destination or intermediate nodes:

- Receives a *route renew* message.
- Receives a *route failure* message.
- Receives another RREQ message indicating a better route: a new route with fewer *heavy_node_number*; or less *nav_sum* with the same *heavy_node_number*; or smaller hop-count with the same *heavy_node_number* and *nav_sum*.

Otherwise, keep the most recently used paths for forwarding packets. Via this approach, our DIAR may achieve the desired objective of improving the network throughput in a fully distributed manner.

4 Simulation Settings

In order to be consistent with previous works [5] and [6], we have exploited the following parameters in our simulations.

- There are various numbers of nodes in an area with length and width of 670 meters. The nodes are located according to a *Poisson* point process over the plane.
- The mobility model is the random *waypoint* model [5]. Each node moves from a random location to a random destination with a randomly chosen speed (uniformly distributed between 0 and 20 meter/sec).
- The traffic sources are UDP Constant Bit Rate (CBR) and the communication pairs are randomly chosen from the entire network.
- The number of source-destination pairs and the packet sending rate of each pair is varied to change the offered load in the network. Each pair of UDP session starts at a staggered time.
- Every single simulation run lasts for 300 simulated seconds.
- We fixed the packet size to 1024 byte.
- Radio link bandwidth is 2Mbps with 250 meter nominal range in maximum.

5 Simulation Results

We have implemented DIAR in *ns-2* [18] with its wireless extensions to evaluate the performance of DIAR. In the first scenario, the networks contain 30, 40 or 50 nodes with 6 to 10 CBR traffic communication pairs. The throughput (Kbps), which is defined over all data packets successfully received only at the destination nodes, is obtained by averaging over all the flows in all given runs. The average improvement of total throughput of DIAR compared with AODV is around 15%; For the best case, the improvement of the total throughput is about 30%. Details are shown in Figures 2, 3 and 4.

Next, in order to give a higher level view on the throughput improvements, we then compare the total throughput for different numbers of nodes ranging

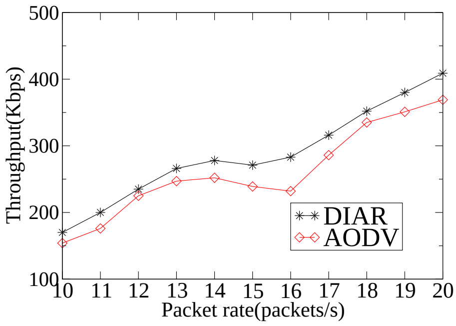


Fig. 2. Throughput vs. packet rate in 30 nodes.

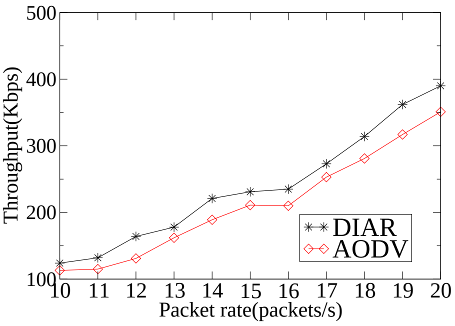


Fig. 3. Throughput vs. packet rate in 40 nodes.

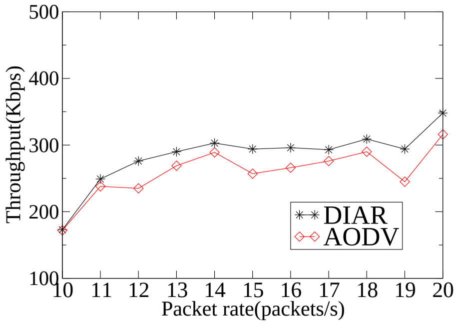


Fig. 4. Throughput vs. packet rate in 50 nodes.

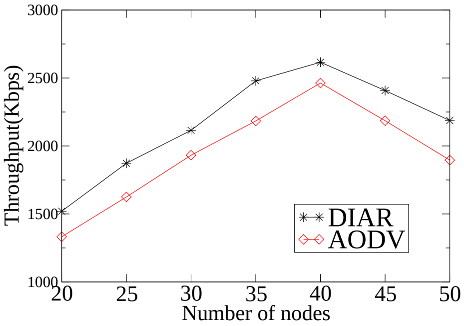


Fig. 5. Total throughput vs. the number of nodes.

from 20 to 50 at a step of 5. The average improvement of the total throughput is 13%; For the best case, the improvement of the total throughput is 29%. Detailed information is given in Figure 5.

From our simulation we draw the following conclusions: (i) The throughput improvement is the best at moderate traffic loads and is negligible at very low or very high loads; (ii) The total throughput improvement is not as high as expected because there does not exist many better routes, i.e. DIAR ends up selecting the same path as AODV. One potential solution to this problem is to apply power control mechanism to increase the spatial reuse level so that more paths could become available. (iii) NAVC is sensitive under highly dynamic situation, which leads to unnecessary rerouting. Solving this problem needs to investigate the appropriate mapping between NAVC and the hop-count.

6 Conclusions and Future Work

In this paper, we have derived an interference aware metric NAVC and proposed a dynamic interference aware routing protocol DIAR for MANET. Our protocol is fully distributed, which exploits the MAC layer information to make routing decisions. We have theoretically and experimentally shown that DIAR is interference-aware and it improves the network throughput. As a part of future works, we will investigate better equations regulating the mapping between NAVC and delay, and NAVC and available bandwidth. We also propose to apply our DIAR mechanism to wireless sensor networks.

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