Interference aware metric for dense multi-hop wireless networks

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***Abstract*— A key issue impacting the performance of multi-hop wireless networks is wireless interference among neighboring nodes. In this paper, we study the impact of interference on mean delay and available bandwidth residing at wireless nodes, and present a novel interference aware metric, named Network Allocation Vector Count (NAVC). The design of NAVC as a metric for the AODV routing protocols, as well as a metric for transmit power control are described in detail. Our simulations demonstrate the poor performance of minimum hop-counts routing protocols, and confirm that NAVC based routing protocol can greatly improve performance. The average throughput increases by up to 29% for UDP CBR traffic. For scenarios of densely deployed nodes, the throughput improvement is often a factor near two, suggesting that NAVC will become more useful as networks grow larger and paths become longer. These approaches are essential for emerging applications such as sensor networks where interference is heavy and bandwidth is limited.**

I. INTRODUCTION

A group of autonomous wireless nodes that wish to communicate may self-organize into a multi-hop wireless network or an ad hoc network, which neither has a fixed infrastructure nor a central server. Each node acts as a router to discover and maintain routes to other nodes. Usually, the nodes are powered by battery, and have a fixed transmission range.

In multi-hop wireless networks, communication between nodes takes place over radio channels. As long as all nodes use the same frequency band for communication, any node-to-node transmission will add to the level of interference experienced by their neighborhood nodes. As a result, network capacity, connectivity, link quality, and bandwidth availability vary dynamically on a variety of timescales in different parts of the network. These problems are compounded further when communicating nodes are not within direct wireless transmission range of each other, and as the network size grows.

It is shown by Gupta and Kumar [1] that the fundamental reason that leads to the degradation of performance as number of nodes increases is the need for every node to share radio channel among its neighbors. Therefore, finding practical wireless interference aware metric for network layer to make routing decisions is critical since contention from neighboring nodes for the shared radio channel is severe when the nodes are densely deployed.

Much of recent routing protocols [2] and [3] usually choose routes with the minimum hop-counts ignoring the possibility that a longer path might offer higher throughput, or arbitrary one among the different paths of the same minimum hop-counts regardless of the often large differences among those paths. Particularly, in a dense network where there may exist many paths with same minimum length, the pure hop-counts metric may choose routes that have significantly less capacity than the best paths that exist in the network. Das *et al.* [4] show that these routing protocols only achieve a small portion of network capacity. For example, in one of their simulated network of 100 nodes with 2Mbps link, the throughput of each node is on the order of a few kilobits per second.

To address these issues, Douglas *et al.* develop a high-throughput path metric called Expected Transmission Count (ETX), which is obtained from link loss characteristics [5]. Besides, power aware routing metric is proposed in [6], which includes energy consumed per-packet, time to network partition, and variance in battery life of nodes.

However, these proposed metrics pay little attention to employ interference information to build paths, which is the key issue impacting performance. The impact of interference on performance multi-hop wireless network has been extensively studied in [7]. Nevertheless, all these state-of-art works limit their work in theoretical analysis on impact of interference without a proper metric derived, which suggests that there is opportunity for achieving throughput gains by employing an interference aware routing protocol.

In addition to interference aware routing, Shepard [8] proposed an efficient distributed channel-access technique based his novel model to analysis interference in large dense packet radio networks. He considered limits on capacity imposed by aggregate interference from many senders spread over a large area and pointed out that capacity can be increased with minimum-energy routing. Our work, in contrast, focuses on interference aware metric to be available with the existing 802.11 channel access algorithm, which can not easily support minimum-energy routing.

Our work is different from previous work in that it is the

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first practical interference aware metric not only for routing in network layer, but also a metric for performing transmit power control in physical layer. The main contributions of the paper are the followings: (i) We propose a novel interference aware metric named Network Allocation Vector Count (NAVC) for multi-hop wireless network. (ii) The design of NAVC as a routing metric for the AODV is described in detail. (iii) We develop a fully distributed transmit power control policy, which functions as a part of the routing protocol, based on the metric and number of neighboring nodes. (iv) We show that in scenarios of densely deployed nodes offered with moderate high traffic load, our NAVC driven AODV outperforms traditional AODV though the former uses longer paths. (V) Finally, we demonstrate using NAVC can substantially increase the network lifetime in the cases of densely deployed network.

The reminder of this paper is organized as follows. In Section II, we develop our system model considered for the interference analysis, from which our metric is derived. The routing scheme with the proposed metric is discussed in detail in Section III. In Section IV, the models and parameters used for simulation are described in detail. Section V demonstrates the effectiveness of our proposed scheme with simulation results under different scenarios. Finally, we draw some conclusions and future perspectives in Section VI.

II. INTERFERENCE ANALYSIS AND METRIC

In this paper, we adopt the point-to-point coding model of [1], which means that at any given time, a receiver only decodes messages from one sender, considering simultaneous transmissions purely as noise, and similarly, at any given time, a sender transmits information only to one receiver. We focus on the aggregate interference imposed by both newly generated traffic per node, and relay traffic that is hopping from a source to a destination throughout the network.

A. *Interference analysis*

It is known that the primary Medium Access Control (MAC) technique of IEEE 802.11 is called distributed coordination function (DCF). It uses a random back-off procedure to resolve medium contention conflicts and a virtual carrier-sense mechanism that exchanges request-to-send (RTS) / clear-to-send (CTS) frames to announce the impending use of the medium via setting the Network Allocation Vector (NAV) value.

Once a node hears other nodes transmission, its NAV will be set to busy state and this node has to keep silence for a duration equal to the *Duration-ID* field in the header. The higher the traffic rate is, the larger the accumulated NAV value will be, and vice versa. Therefore, the NAV in 802.11 MAC protocol can be a good representative of the surrounding traffic. Consequently, the impact of interference suffered by a node can be obtained by calculating NAV in certain means.

B. *Interference metric*

With comprehensive simulations and analysis, we have found that there is a fixed relationship between NAVC, which is computed using equation (1), and the available bandwidth and average delay. This relationship is insensitive to user number and traffic pattern. Each node will periodically compute its NAVC value by collecting the NAV value from MAC layer. Thus, as long as we can sense the NAV value, we can estimate the delay characteristics by equation (2) in the Fig. 1(a). In addition, if we know the average packet length, the available bandwidth (BW) can be approximately estimated using equation (3) in the Fig. 1(b).

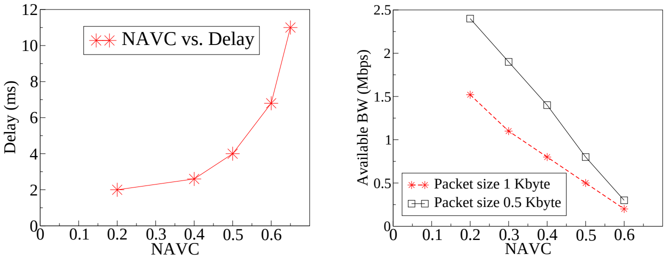
$$NAVC = \frac{\sum_{t_i=t_\mu}^{t_i=t_\nu} NAV_{t_i}}{t_\nu - t_\mu}. \qquad (1)$$

If NAVC is less than 0.20, the delay is usually small and insensitive to the number of users. When the NAVC is greater 0.65, it usually indicates the node has been overloaded.More detailed information about NAV occupation mapping to mean delay and available bandwidth can be found in our previously paper [9].

$$Delay(x) = \begin{cases} 2ms, & \text{if} \quad x \leq 0.2 \\ 2e^{7.9(x-0.2)^2}ms, & \text{if} \quad 0.2 < x \leq 0.65 \end{cases} \qquad (2)$$

$$BW(L, x) = (0.0024L + 0.9) - (0.0036 + 1.4)x, \qquad (3)$$

where L is the packet length and x represents the NAVC.



(a) NAVC vs. Delay

(b) NAVC vs. Available Bandwidth

Fig. 1. NAVC vs. Delay and Available Bandwidth.

In next section, we will show how our routing scheme construct paths and perform transmit power control with our proposed metric.

III. NAVC-DRIVEN AODV

NAVC, as a generic interference aware metric, can be used in general wireless multi-hop routing protocol. As an extension to AODV [2], NAVC-driven AODV is also an on-demand algorithm, building routes using a route request route reply cycle with the interference aware metric. The key idea is to avoid selecting a route, which has nodes in the heavy interference neighborhood so that the energy and time spent in contention is minimized.

With this metric, routes selection and power control decision can be made at the network layer with interference information obtained from link layer. Specifically, the modified routing protocol contains two operating modules, route discovery and transmit power control.

A. *Route Discovery*

The route discovery includes three components, namely the route request, route reply and route maintenance.

1) Route request: When a source node desires a route to a destination for which it does not already have a route, it broadcasts a ROUTE REQUEST ($RREQ$) packet across the network. There are two additional options namely $heavy\_node\_number$ and nav_sum in the $RREQ$ messages besides all the options in the normal AODV $RREQ$ message. After receiving the $RREQ$ packet, the nodes other than the destination node have three possibilities:

- If its NAVC is larger than 0.65, increase the option $heavy\_node\_number$ by 1 because this node is considered as a heavy interfered nodes. In addition, the option nav_sum by the square of the NAVC value. The purpose of using square value is to differentiate the NAVC value by adding increasing weight.
- If its NAVC is between 0.25 and 0.65, increase only the option nav_sum by the square of the NAVC. Whenever a node's NAVC is less than 0.25, it does not make significant difference in terms of average delay and residual bandwidth for a link.
- If none of the above requirements is satisfied, continue broadcasting this $RREQ$ without making any modification to these two options.

2) Route reply: When destination node receives any valid $RREQ$ message without timeout, it will send the ROUTE REPLY $RREP$ message immediately in order to decrease the route discovery delay. It's possible that there will be multiple $RREP$ for the same communicating pair. However, the source is responsible to select the path with least $heavy\_node\_number$ and nav_sum. $heavy\_node\_number$ gets higher priority compared to nav_sum in path selection.

3) Route maintenance: Whenever any one of following conditions is met, the route update process will be activated at source, destination or intermediate nodes.

- Receives another valid RREQ notifying a better route: which means another route with lower $heavy\_node\_number$; lower nav_sum with same $heavy\_node\_number$; or shorter hops with the same interference condition.
- Receives a ROUTE ERROR message.

Otherwise, keep the latest used valid path for forwarding packets.

B. Transmit power control

The primary goal of reducing transmit power here is to increase the spatial reusability because the sensing range is much larger than the transmission range. Secondly, it can save certain amount of energy because transmission to a distant device at higher power level may consume a disproportionate amount of power in comparison to transmission to a node in closer proximity [10].

Each node will perform transmit power control according to its NAVC value, node degree, and neighbors' NAVC value, which are obtained via using one hop broadcast $HELLO$ messages. The $HELLO$ message contains the node's NAVC value and current transmit power level (denoted by Cur_{tr}). Upon receiving the $HELLO$ message, the receiving node can measure the received signal strength so as to compute the minimum transmit power level (denoted by Min_{tr}) necessary to reach the source node. If the receiving node's Cur_{tr} is larger than Min_{tr}, the source is qualified as a neighbor. Otherwise, the source node is not considered as a neighbor because this link is unidirectional.

Whether to reduce or raise its Cur_{tr} is made according to following power level adjustment eligibility:

1) If Cur_{tr} can cover eight or more neighboring nodes, which means there are more than enough neighboring nodes to guarantee connectivity [11] and [12], the node should reduce its transmit power to the next available level.
2) If Cur_{tr} can cover over four nodes while less than eight nodes, and half or more of these neighboring nodes' NAVC exceeds 0.65, which indicates that its neighborhood is experiencing serious interference that might be caused by this node. Subsequently, this node will reduce its transmit power to the next available level. Then, update all the recorded the neighbor list and route entries constructed under last used power level.
3) If Cur_{tr} only can cover less or equal than four neighboring nodes, this node needs to increase its transmit power to the next available level in order to maintain the connectivity.
4) If a node's NAVC is low, which possibly means it continues obtaining the radio channel, there is a danger that its neighboring nodes will be captured. On the contrary, if a node continually fails in trying reserve the channel, its NAVC could extremely large, it should raise its Cur_{tr} in order to break the possible capture effects.
5) Every transmit power adjustment should be done some time after the last one so that the problem of frequently oscillation can be mitigated.

IV. SIMULATION PARAMETERS

Our simulation is based on the Network Simulator (*ns*) developed at Lawrence Berkeley National Laboratory [13] with its wireless extensions developed by the Monarch Project. For all the simulations, we have used AODV implementation of *ns-2* along with our implementation of NAVC-driven AODV for *ns-2*. To be consistent with previous work [4], [5], [10], [14], [15], [16], following parameters have been used in our simulations.

A. Traffic and mobility model

- The traffic sources are UDP Constant Bit Rate (CBR). The communication pairs are randomly chosen from the entire network and each pair of UDP session will start at staggered times. We fixed the data packet size to 512 byte.
- The mobility model uses the random *waypoint* model [14] in a field with length and width of 1000m x 450m. The nodes are located according to a Poisson point process over the plane. Each node moves from a random location

Tx level 1	Tx level 2	Tx level 3	Tx level 4	Tx level 5
1201mW	1207mV	1237mW	1315mW	1482mW

TABLE I

”Tx” (Transmit) power values of 2Mbps.

to a random destination with a randomly chosen speed (uniformly distributed between 0 and 10 meter/sec).

- There are multiple runs with random parameters in order to obtain results without losing generality and every single simulation run lasts for 300 seconds.

B. *Wireless model*

- The propagation model is based on a *two-ray ground* model, which is appropriate for outdoor environments where a strong line of sight signal exits between the transmitter and receiver nodes and where the antennas are omnidirectional.
- Radio link bandwidth is 2Mbps with 250 meters nominal range in maximum.

C. *Energy model*

- We assume nodes are capable of dynamically adjusting the transmit power used to communicate with other nodes.
- According to [15] and [17], energy consumption ratios among different working modes idle:receive:transimit used here is 1:1.25:1.875.
- The *Aironet PC4800* wireless LAN card has five discrete Radio Frequency (RF) output power levels (RF_level) [10]. Therefore, there are also five RF_levels in our simulation, namely 1.3, 7.2, 37, 115, and 282 milliwatts so that the radios can reach 50, 100, 150, 200, 250 meter respectively[1].
- The transmit power value (*Tx*) is computed via equation (4) and listed in Table I[2]:

$$Tx = 1200 + RF\_level. \tag{4}$$

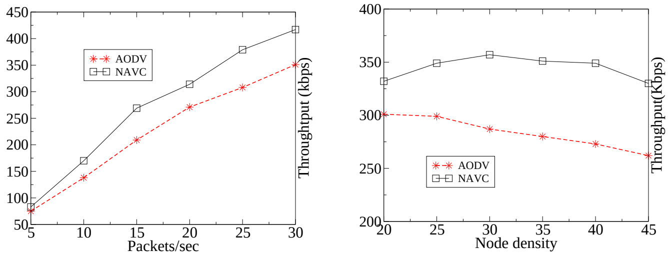
- At the beginning of simulation, each node has an initial energy of 300 Joules and uses the maximum transmit power level as the default.

V. RESULTS

The performance of a routing protocol can be measured primarily by the achievable throughput given a set of constrained resources. Other metrics such as the network lifetime and the average hop-count are also important in providing insight for better understanding the behavior of the protocol.

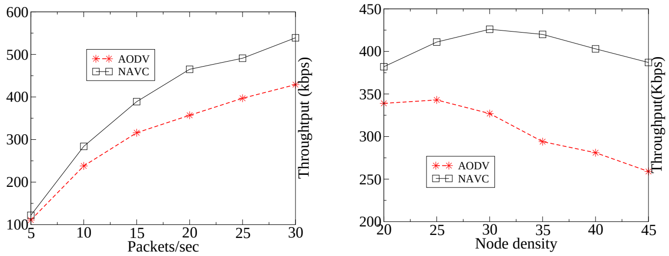
A. *Throughput*

Here, *throughput* refers to all the data bytes received per second at the destination node without duplication. In this section, we will evaluate NAVC's ability to improve the throughput under different traffic load, degree of *node density*. The *node density* [15] is defined as the number of nodes that are not source or destination per radio range (i.e., an area of $250^2 \times \pi$ square meters).



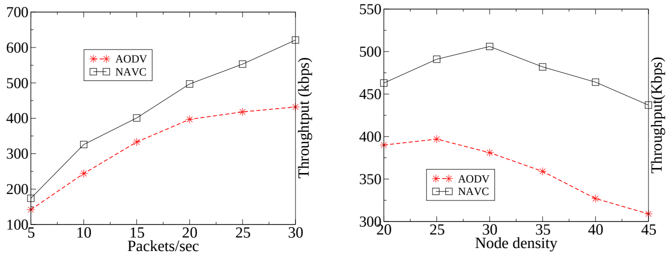
(a) 5 pairs varying load

(b) 10 pairs varying node density



(c) 8 pairs varying load

(d) 15 pairs varying node density



(e) 10 pairs varying load

(f) 20 pairs varying node density

Fig. 2. Throughput comparison of NAVC and AODV.

The first set of simulation is performed using 5, 8, and 10 communication pairs with different offered load. The packets rate ranging from 5, 10, 15, 20, 25, to 30 packets/sec because we want to offer reasonable high load to the network. By default, pause time of is 60 seconds. The detailed results are shown in Figure 2(a), Figure 2(c), and Figure 2(e).

The second set of simulation is performed under *node density* of 20, 25, 30, 35, 40, and 45. There are 10, 15, and 20 communication pairs used with a fixed packets rate of 10 packets/sec. The detailed results are shown in Figure 2(b), Figure 2(d), and Figure 2(f).

These results demonstrate the following facts: (i) NAVC exhibits higher throughput improvement under heavier traffic load in general. (ii) The denser the network is, the higher the throughput improvement the NAVC can achieve. For the best case, the improvement of the total throughput is around a factor of two. (iii) The throughput improvement is the best at moderately heavy network load and negligible at very low load. (iv) NAVC works the best when *node density* is not too low nor too high. (v) The average throughput increases by up to 29% for UDP CBR traffic.

B. *Network lifetime*

Network lifetime is defined as the time it takes for the first node to drain out its energy. The larger this value, the more energy-efficient the routing protocol is, and vice versa. The results, shown in Figure 3(a), are obtained from one singe set

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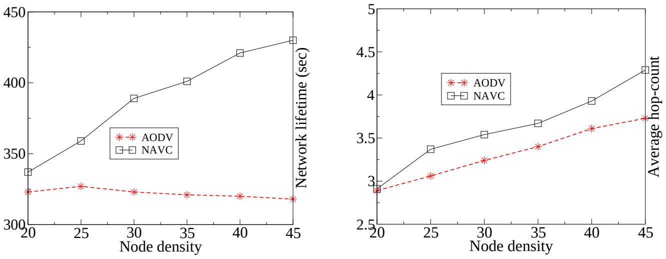
[1] These values are computed via the *two-ray ground* model in *ns*-2.

[2] The value 1200 sums the energy consumed by different components of WLAN card [16].

experiments with 15 communicating pairs in *node density* of 20, 25, 30, 35, 40, and 45. The traffic source nodes starts with 2000 Joules so that the traffic load can last for enough time.

The average improvement of network lifetime is about 27%, which could be further improved if we not only reduce the transmit power but also switch to power saving modes such as *sleeping* mode. Typically, more power is consumed during the transmission of packets than the *receiving* or during *Idling* periods. Nevertheless, as it is shown by [17], the *Idle* mode occupies significant part of the total energy consumption because in most time, even during *idle*, the radio electronics must be powered and decoding to detect the presence of an incoming packets.



(a) Network lifetime

(b) Average hop-count

Fig. 3. Network lifetime and Average hop-counts comparisons.

C. *Average hop-count*

It is shown in Figure 3(b) that NAVC often finds paths with larger hop-count compared to AODV, particularly between distant nodes. When the load is light or network is sparse, NAVC selects almost the same length paths as AODV does. This is because either the traffic is not heavy enough to cause heavy interference nodes or there are lack of forwarding nodes to form better paths. As the traffic load and *node density* increase, NAVC starts to choose better paths with less interference and larger hop-count.

However, the difference of the average hop-count between NAVC and AODV is not too large because non-local traffic patterns in which the average distance grows with the network size result in a rapid decrease of per node capacity [18]. By conducting transmit power control, NAVC is able to reduce the interference so that more nodes become available for forwarding packets for others. Consequently, new paths are created and some of them have similar or even shorter length compared to those paths constructed by AODV using minimum hop-count metric.

VI. CONCLUSION AND FUTURE WORK

In this paper we have presented and evaluated a novel interference aware metric for dense multi-hop wireless network. This metric is used by network layer to make routes selection, and physical layer to conduct transmit power control in fully distributed manner, while only the interference information from MAC layer is exploited. It has been shown experimentally that the NAVC-driven AODV is interference aware and improves the system performance in terms of throughput and network lifetime, though using slightly longer paths to deliver packets as compared with AODV.

As a part of our future work, several aspects of NAVC could be further improved: its mapping relation to the number of hop-counts when functioning as a metric for routing; its effectiveness when nodes are with high degree of mobility and different mobility models; NAVC's ability to handle networks with huge amounts of nodes. Besides, we are continuing to investigate the benefits of interference aware routing under more complex scenarios like sensor network.

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