Attainable Capacity Aware Routing Metric for Wireless Mesh Networks

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***Abstract*— We propose a new metric, called the attainable capacity (ACAP) aware routing metric, to address issues on throughput, interference and load imbalance in wireless mesh networks. In contrast with previously proposed metrics, ACAP takes into account the busyness and shared nature of the wireless channel together with the combined effect of the transmission rates of the nodes that share it. Accordingly, paths with highest attainable capacity are chosen as the best paths. In the process, regions with higher degree of congestion are also avoided to improve throughput and load distribution across the network. We present an analysis of the above interaction and uses it to define ACAP. We expect ACAP to be significantly better than existing metrics in discriminating congested regions and in finding higher capacity routes. Like many of these existing metrics, APAC is suitable to both multi-radio and multi-channel wireless mesh networks.**

Keywords* - *wireless mesh networks, routing, routing metric, congestion awareness, attainable capacity

I. INTRODUCTION

Wireless mesh networks (WMN) have emerged to be a cheaper and flexible alternative for quick deployment of wireless services for a large variety of applications such as broadband home networking and automation [1] , community and neighborhood networking [2], transportation systems [3], spontaneous (emergency/disaster) networking[4], and others.

However, despite advances in this field, many research challenges remain [5]. One issue is the use of routing metrics that do not scale well, such as hop count: network throughput drops significantly as the number of nodes or hops increases in the network [6]. This paper proposes the attainable capacity (ACAP) aware routing metric to address issues on throughput, interference,load imbalance, and congestion problems as networks grow.

The rest of the paper is organized as follows: Section II discusses the motivation and related work, while Section III presents an analysis that lead to the design of ACAP. Section IV discusses ACAP's implementation details. Finally, Section V concludes.

II. MOTIVATION AND RELATED WORK

In both wired and wireless networks, a routing algorithm's function is to discover a path for a packet to traverse from its source to its destination. A routing algorithm in return may find more than one route. To decide which is best, it uses routing metrics [7]. In a multi-hop WMN, routing becomes more critical than in wired networks, because the wireless medium is shared and is highly dynamic [8]. Different packet flows may interfere with each other even when they do not necessarily traverse the same path, consequently congesting that direction thus lowering throughput significantly.

The simplest and most commonly-used routing metric in WMN is the hop-count metric, as used in DSR [9] , AODV [10], and DSDV[11]. It reflects the path- length in hops, and in many cases the shortest physical path is used. However, it is insensitive to the quality of links between hops and to the degree of congestion on the link [12].

ETX [12] and ETT [13] on the other hand are able to measure quality of links but not congestion. Some load balancing protocols like WLAR [14] and DLAR [15] can avoid loaded nodes, but cannot determine link capacities.

Among the metrics that are similar to ACAP in functionality, ALARM [16] identifies paths with better capacity and nodes with less load. However, it cannot measure interfering transmissions from neighboring nodes. Thus, it may avoid loaded nodes but not necessarily congested regions of the network. The ILA routing metric [17] claims to have solved this issue. However, its metric measures congestion in terms of the average load of nodes within a collision domain (see Fig. 1). In this case, it will not be able to distinguish between regions having more interfering nodes over regions having less, as long as the average loads are the same. Thus, it can not determine capacity accurately since a domain with less nodes that share a channel can provide higher achievable data rates. ACAP, on the other hand, solves these issues by estimating the achievable capacity in proportion to the load of the channel, and in conjunction with the transmission rates (minus packet losses) of the individual nodes that share it.

III. DESIGN OF THE PROPOSED METRIC

We begin our analysis by looking at a node *j*'s collision domain. It is comprised of *j's* neighbor nodes within its carrier sensing range that operate on the same channel. All transmissions of these nodes interfere with that of *j*'s. See Fig. 1, assuming circular carrier sensing range.

Because of the shared nature of the channel within *j's* collision domain, the capacity of the link that may be achieved in choosing *j* as a next hop node depends on the activities happening in the channel. If the channel is idle, the achievable capacity is close to the full capacity of the link, less overhead and packet losses. If there are activities in the channel, then the link's achievable capacity is less.

A. Channel Busyness and Utilization

In determining the ACAP of the link in considering a node *j* as the next-hop from a node *i*, we quantify the degree of *busyness* of the channel within *i* and *j's* collision domain. Although other authors define the degree of busyness as the fraction of time the channel is inferred to be busy [18], in our work, we refine this definition of busyness to pertain to the fraction of time the channel is *sensed* (rather than inferred) to be busy.

Busyness, as used in our work, is different from channel utilization. Channel utilization is typically defined as the achieved throughput related to the capacity of the communication medium [7]

[16], which could achieve a maximum value less than 100%, because of overhead, packet losses, and queuing issues. On the other hand, channel busyness is defined as the fraction within a given period when transmission occurs over the wireless medium, which may attain a maximum value of 100%.

B. The Attainable Capacity Aware (ACAP) Routing Metric

In a simulation study, it is observed that channel busyness increases linearly with aggregate input traffic until channel saturates [18]. When the channel is saturated, although input traffic increases, throughput does not increase because all time slots are utilized. In [19], a channel saturates when the aggregate input traffic reaches 80% of the nominal bit rate. In a separate study [20] that looks onto the saturation throughput between a 802.11b access point and a laptop, similar behavior was observed except that the saturation throughput reached only 50 to 70% of the channel capacity (5 different wireless brands were individually tested). In these studies, the input traffic approximates the throughput linearly until saturation. At saturation, as more input traffic is injected, the throughput either hovers around a constant value [18] or asymptotically drops to a lower one [18]. In the context of this work, the studies imply two things. First, that the rated capacity of a channel is never reached even if there is only a pair of communicating nodes, because of packet losses, overheads, and delays. Secondly, it can be said that the capacity that a channel may offer decreases linearly until saturation. The second implication is summarized in Fig. 2. Using methods from analytic geometry [21], the ACAP in connecting to *j* is derived as:

$$ACAP(j) = ACAP(j)_{idl} - CB(j)\left(ACAP(j)_{idl} - ACAP(j)_{sat}\right) \qquad (1)$$

$where:$
$ACAP(j)$ is the attainable capacity $(ACAP)$ in connecting to j
$ACAP(j)_{idl}$ is the $ACAP$ when the channel is idle
$ACAP(j)_{sat}$ is the $ACAP$ when the channel is saturated
$CB(j)$ is the degree of channel busyness of node j's collision domain

ACAP(*i*) is obtained following the same analysis. In turn, the ACAP of the link k between nodes *i* and *j* is defined as:

$$ACAP(k) = \frac{1}{\dfrac{1}{ACAP(i)} + \dfrac{1}{ACAP(j)}} \qquad (2)$$

$where:$
$ACAP(k)$ is the attainable capacity of link between nodes i and j
$ACAP(j)$ is the attainable capacity in connecting to j
$ACAP(k)$ is the attainable capacity in connecting to i

Consequently the attainable capacity of the path between a pair of source and destination is given in 3. If the routing algorithm finds more than one path, it selects the path with the highest ACAP metric.

$$ACAP(P) = \frac{1}{\sum_{k \in P} \dfrac{1}{ACAP(k)}} \qquad (3)$$

$where:$
$ACAP(P)$ is the attainable capacity on path P
$ACAP(k)$ is the actual attainable capacity of link k
k is a link on path P

We do not make any assumption about the operating channel of a collision domain; we only require to consider *i* and *j's* collision domains to operate on the same channel as that of link k. If some collision domains operate over different channels, the analysis would follow the same process. Therefore, (2) can determine the ACAP of a link and (3) can determine ACAP of a path. Thus, ACAP is suitable for multi-radio and multi-channel mesh networks. At the moment, our analysis assumes negligible channel switching cost.

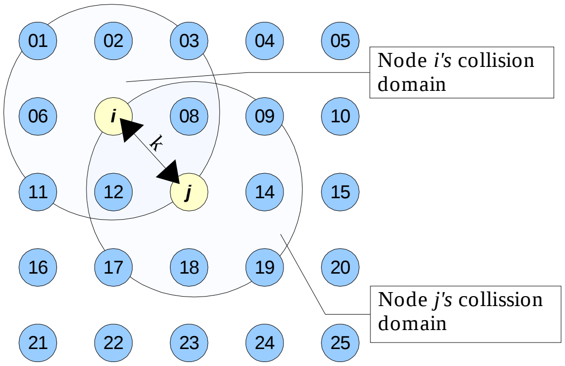

Figure 1: A Wireless Mesh Network with 25 nodes

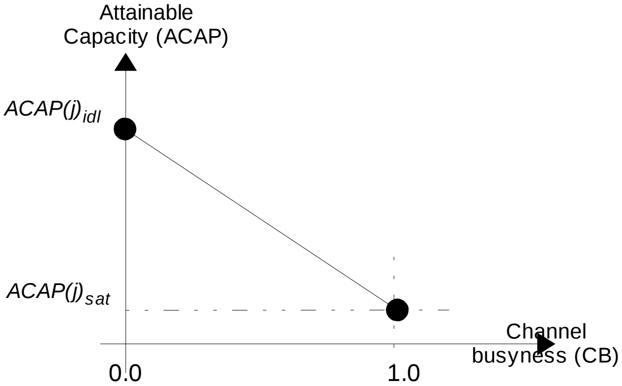

Figure 2: Attainable Capacity (ACAP) vs. Channel busyness (CB)

IV. IMPLEMENTATION

In this section, we define both the attainable capacity and the channel busyness when the channel is idle and when it is saturated. We assume that all nodes in a collision domain have a packet to transmit at saturation. In doing so, we use 802.11 equipped nodes operating using the basic access mode of the distributed communication function (DCF) of the 802.11 [22].

A. The value for the ACAP when the channel is idle (ACAPidl)

When the channel is idle, the ACAP in choosing *j* as the next-hop node can never be more than, and usually is less than, the nominal bit rate of the link between *i* and *j* due to overheads and packet losses [19],[18],[20]. Discounting overheads, but considering packet losses, the ACAP of the link k connecting *i* and *j* when the channel is idle can be defined as:

$$ACAP(k)_{idl} = p_{ij}\, p_{ji}\, r_{ij} \qquad (4)$$

$where:$
$ACAP(k)_{idl}$ is the attainable capacity when the channel is idle
p_{ij} and p_{ji} are the forward and reverse packet delivery ratios
r_{ij} is the nominal bit rate between i and j

Here, we do not include the overhead in the definition of the ACAP because we are not trying to come up with an accurate value for the attainable capacity that a path may provide. Rather, we would like to compute relative values that may be compared between candidate routing paths. The overhead is common to other links and so its effect, hence, the omission is justified.

The use of forward and reverse packet delivery ratios is due to channel asymmetry and to estimate them periodic probe packets can be used [12],[13].

B. The value for the ACAP when the channel saturates

At channel saturation, the 802.11 distributed communication function (DCF) provides equal transmission opportunities among nodes in a collision domain [23]. Following the analysis made in [24],[25], and again discounting overhead but considering packet losses, this value is defined as:

$$r(j)_{sat} = \frac{1}{\sum\limits_{n \in D_j \wedge n \neq j} \frac{1}{p_{nj} p_{jn} r_{nj}}} \tag{5}$$

where :
$r(j)_{sat}$ is the channel's saturation data rate within
j's collision domain
D_j is the set of nodes within j's collision domain
n is a node within j's collision domain
p_{ij} and p_{ji} are the forward and reverse packet delivery ratios
r_{nj} is the nominal bit rate of node n in connecting to node j
j is the node being considered

Rewriting (5) in terms of ACAP, $ACAP(j)_{sat}$ is defined in (6). $ACAP(i)_{sat}$ should be obtained in the same manner.

$$ACAP(j)_{sat} = \frac{1}{\sum\limits_{n \in D_j \wedge n \neq j} \frac{1}{ACAP(nj)_{idl}}} \tag{6}$$

where :
$ACAP(j)_{sat}$ is j's collision domain attainable capacity at saturation
$r(j)_{sat}$ is the channel's saturation data rate
D_j is the set of nodes within j's collision domain
n is a node within j's collision domain
$ACAP(nj)_{idl} = p_{nj} p_{jn} r_{nj}$

However, it should be noted that (6) gives an ACAP at saturation that does not take into account the effect of collision domains of nodes outside the path but whose range overlaps with those of the nodes along the path. We presume that extending the definition to include their effect will increase the complexity of finding the solution. We opted to initially have a workable one, as given by (6) and tackle such scenario as part of a future work.

C. The channel busyness (CB)

Channel busyness in a collision domain is defined as the fraction of time within a given period where the channel is being used for transmission. A previous definition was presented in [18] that seems simpler to implement, because it is obtained from just observing the collision probability within the channel as opposed to actually monitoring the channel for a given period (that we intend to do). However, this may not be accurate since the DCF of 802.11 actually avoids collision through its back-off mechanism, and this value is kept at minimum until saturation point. Nevertheless, their result showed some accuracy even in the presence of other causes of packet loss (like fading). We are currently validating this, as the simplicity of their definition might prove useful in this work.

We intend to monitor activity on the channel through carrier sensing. A node determines the channel as busy when a node (not necessarily the sensing node) is sending a message to another node, or the sensing node itself is actually transmitting data, whether transmission is successful or not. For a given period, (equal to 100ms synchronized with the transmission of the 802.11 beacon frame [22]), the degree of busyness from the perspective of a node *j* is defined in (7).

$$CB_j = \frac{\sum T_{busy} + \sum T_{transmitting}}{\sum T_{idle} + \sum T_{busy} + \sum T_{transmitting}} \tag{7}$$

where :
CB_j is the channel busyness ratio from within j's collision domain
$\sum T_{idle}$ is the duration that node j senses the channel as idle
$\sum T_{busy}$ is the duration that node j senses the channel as busy
$\sum T_{transmitting}$ is the duration that node j is transmitting frames

Here T_{idle}, T_{busy} *and* $T_{transmitting}$ are computed as follows [22],[18]:
T_{idle} = number of slot-time sensed as idle * 20 µs
T_{busy} = number of slot-time sensed as busy * 20 µs
$T_{transmitting} = T_{successful} + T_{collision}$
$T_{successful}$ = data/bitrate + ack/bitrate + SIFS + DIFS + 2* T_{pr}
$T_{collision}$ = data/bitrate + ack-timeout + SIFS + DIFS + 2* T_{pr}

Based on 802.11b[22] values and without using RTS/CTS mechanism, the constants above are slottime = 20µs; ack = 14-byte frame; ack-time out = 22µs, (as used in [26]); SIFS (short interframe sequence) = 10 µs; PIFS (point interframe sequence) = SIFS + slottime = 30 µs; DIFS (distributed interframe sequence) = SIFS + 2 x slottime = 50 µs; T_{pr} = 96 µs, is the PLCP (Physical Layer Convergence Protocol) preamble and header. The short PLCP is put here, since it is used for most available nominal bit rates in 802.11

DIFS is the amount of time a station must sense a clear radio before beginning a new transmission sequence. SIFS is the amount of time a station must wait before sending or beginning to receive a ACK frame, RTS, or CTS. T_{pr} is the time occupied by the PLCP header introduced by the physical layer for mapping MPDU (mac protocol data unit) into a suitable PDU (Physical Data Unit)[23].

However, we need to smoothen the impact of the sudden changes in traffic. We employ a moving average for the channel busyness using a tunable parameter α. To make it simple, we will initially use 0.5. The channel busyness is, thus, defined as:

$$CB_j(t) = (1-\alpha) \times CB_j(t-1) + \alpha \times CB_j \tag{8}$$

where :
$CB_j(t)$ is the current value of the moving average of the channel
busyness ratio within j's collision domain
α is a tunable parameter : $0 \leq \alpha \leq 1$, here 0.5 is used
CB_j is the current computed channel busyness
$CB_j(t-1)$ is the previous smoothed average channel busyness
t refers to the current measuring period

D. ACAP Summary

ACAP is a measure of the attainable capacity of a link based on the shared nature and busyness of a channel. The more busy a channel, the less it is capable of accepting input traffic without dropping packets. Its shared nature, on the other hand, is affected by the quantity of nodes sharing the channel and their respective transmission rates. The more nodes that share a channel, the less share a node gets on the channel capacity. Further, in a self-configuring WMN that implements a distributed channel access mechanism, similar to 802.11's DCF, the node with the lowest nominal-bit-rate penalizes the high-bit-rate ones: at saturation, each node gets a bit rate that is no more than the lowest bit rate [27]. Put together, using the analytical model presented above, the ACAP of a link is obtained. The ACAP of the path becomes the sum of the ACAP's of the links that comprise the path. This value is then used as basis for choosing the best path among candidate paths.

ACAP is suitable for both multi-radio and multi-channel wireless mesh networks as pointed out earlier. We compute the ACAP one link at a time, per collision domain.

V. CONCLUSION AND FUTURE WORK

We proposed a new routing metric called the Attainable Capacity Aware routing metric (ACAP) for wireless mesh networks. ACAP estimates the attainable capacity of a link based on the shared nature and busyness of a channel within a link's end-nodes' collision domain. The shared nature of the channel is affected by the quantity of nodes within the collision domain and their respective transmission rates. The quality of the links based on packet losses has also been incorporated into the ACAP metric

We expect ACAP to perform better than recently proposed routing metrics, such as ALARM and ILA, because it can better discriminate congestion and accurately estimate capacity by incorporating the busyness and shared nature of the channel, and in conjunction with the quantity of and respective nominal bit rates (minus packet loss) of contending nodes.

Our current work focuses on testing our metric in a simulation set-up similar to [19] and [17] then implementing the experiment in actual test-bed whose set-up is similar to [28].

In the future, we intend to include a broader framework that takes into consideration the effect of overlapping domains. Other mechanisms to account for channel busyness will also be explored .

ACKNOWLEDGMENT

This work has been supported by the Engineering Research and Development for Technology (ERDT) Consortium, Department of Science and Technology – Science Education Institute (DOST-SEI), Republic of the Philippines.

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