A routing metric for floor acquisition oriented medium access schemes

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Abstract — In this paper, a routing metric for shortest path routing is described. The metric is particularly crafted for a floor acquisition oriented medium access scheme, such as IEEE 802.11 DCF, where nodes around communicating node pairs get blocked. Two variants of the metric are described, one for systems with and one for systems without rate control. Performance is evaluated and compared to two conventional metrics (minimum hop and inverse rate metrics). Implementation issues related to the metric are also discussed.

Index terms — Ad hoc networks, Multihop network, Routing metric, Floor acquisition, Maximum access scheme, IEEE 802.11.

I. INTRODUCTION

Mobile ad hoc-, mesh-, and multihop networking [1], [2] are active research areas, often envisioned for future wireless systems as increased data rates, capacity and ability to connect nodes out of reach of each other is promised. A basic research challenge in this context is to design more efficient wireless routing schemes than offered by existing methods. Another currently active research area is centred around the IEEE 802.11 standard and its core MAC protocol denoted Distributed Coordination Function (DCF) [3], [4]. This MAC protocol is of a type that can broadly be characterized and will be refereed to as a floor acquisition oriented medium access like (FAMA-like) scheme. The objective here is to look closer at routing in wireless networks that operates with FAMA-like schemes in general, and with IEEE 802.11 DCF in particular.

In the following, FAMA-like methods are defined as those with a medium access schemes that, during the time of sending a packet from a transmitting node to a receiving node, prohibit nodes around both the transmitter and the receiver to be in communication with any other node. Typically, this blocking operation is ensured by using identical transmit powers and exchanging small control packets, between the transmitter and the receiver, which surrounding nodes may overhear. Examples of FAMA-like access scheme are FAMA, SRMA, MACA(W), and the already mentioned IEEE 802.11 DCF (similar to DFWMAC), see e.g. [5], [6] for more examples. In IEEE 802.11 DCF, the well-known RTS-CTS frame exchange prior the data transmission indicates a blocking durations that overhearing nodes must adhere to. The basic idea of FAMA-like protocols is sketched in Fig. 1, showing a sender blocking seven nodes and the receiver blocking five nodes. In total ten nodes are blocked apart from the sending and receiving node.

A fundamental part of networks employing wireless routing is that data packets shall efficiently find their way from their source nodes to their respective destination nodes. Commonly, this is solved by a heuristic approach where routes are determined with a shortest path algorithm, and associated protocols, and data packets are subsequently forwarded along those routes. Typically, each link has an associated cost (a link cost) that is used in calculating the total route cost. The dimension of the link and route cost may for instance be hops, (per bit) transmit time, path loss, (per bit) energy, emitted power/energy interference, and this is what is here denoted as “routing metric” [10]-[14]. Hence, the metric is the physical property to be optimized, whereas link and routing costs are the values of the metric for links and routes respectively.

In examining previous work on routing metrics, it appears that no metric seem to be have been designed specifically for FAMA-like schemes. Yet, in designing routing metrics, it is vital to account for any medium access scheme specifics. This is in particularly true for FAMA-like methods, where both the sender and receiver acquire floors, i.e. both prevent other nodes from communicating. Accordingly, this paper proposes two new routing metrics that are specifically crafted for FAMA-like schemes. Those metrics account for the number of blocked nodes as well as the number of blocked nodes times the inverse rate of blocking, respectively.

As a first step in evaluating the performance of the proposed metrics, the performance is indirectly evaluated by examining properties of shortest path trees created in simulations, rather than directly studying the performance with actual traffic being forwarded along the routing trees. The per route and per node performance is determined with respect to the sum of the blocking duration times the number of blocked nodes and the sum of the blocked node duration, respectively. Two metrics, a hop and an inverse rate metric, are used as reference cases. It is observed from simulations that the metrics involving the number of blocked nodes appears to perform better than the metrics without a dependency on the number of blocked nodes. It is also observed that inverse rate based metrics appears better performing than non-inverse rate dependent metrics. The proposed metrics also reduce the variance of node blocking time.

The rest of this paper is organized as follows. First, more background on routing and routing metrics is given in II. The proposed routing metrics are introduced in section III, and the evaluated through simulation in section IV, whereas conclusions are drawn in section V.
II. PRELIMINARIES AND RELATED WORK

In this section, a short sketch is given on how distributed wireless routing may operate and some previous work on routing metrics is presented.

A. Distributed wireless routing

In distributed wireless routing scenarios, such as for mobile ad hoc networks based on shortest path routing⁸, it is often convenient to divide the routing function in several sub-functions such as topology control, route determination, and forwarding. The topology control ensures that a node has knowledge of, and contact with, a set of neighbours. The forwarding function ensures that a received data packet is forwarded, possibly by first performing QOS or channel dependent scheduling, to a subsequent node. In this section, the concern is primarily the route determination function, where routes could be set-up either reactively⁹ (on-demand) or proactively (table-driven). To determine routes, an algorithm, link costs, a selected routing metric, and a protocol to disseminate and exchange the computed routing information are typically needed. Below, a typical route determination algorithm and associated protocol are sketched.

The distributed Bellman-Ford algorithm [9] is used to determine the shortest paths. For the Bellman-Ford algorithm, the cost $C_i$ of a node $v_i$ for each destination $d$ is determined through the distributed Bellman-Ford equation that is iterated and updated continuously to converge to the shortest path solution as well as adapting to changes in topology due to mobility. The equation is (omitting the iteration index)

$$C_i^{(d)} = \min_{v_j \in N_i} \{\Delta C_{ij} + C_j^{(d)}\}$$

(1)

, where $v_j \in N_i$ is the neighbour index of neighbour nodes belonging to node $v_i$, $C_j$ is the cost for neighbour $v_j$ to reach destination $d$, and $\Delta C_{ij}$ is the cost to go from node $v_i$ to $v_j$. Here, a node may be considered to be a neighbour if the link quality meets some desired fidelity level.

The number of iterations may be limited to an integer number, thereby upper limiting the number of hops, e.g. a maximum of two hops. It is also sensible to restrict the cost from propagating all over the network. For example, a maximum number of hops may only be allowed or only nodes within a certain region may participate in executing the shortest path algorithm. The Bellman-Ford algorithm is easily implemented in a distributed manner. In essence, neighbouring nodes exchange routing lists. Each routing list contains multiple entries, where each entry specifies a destination node as well as the routing cost to that node. The routing list is typically sent in a packet, often denoted as a Hello packet. A node receiving a routing list, checks whether each entry offers a more optimum route than the nodes own list indicates. Often, timestamps or sequence numbers are included together in the entry to ensure that the new cost information does not contain outdated information.

B. Routing metrics

Two basic approaches can be followed for routing metrics, i.e. the metric is dependent or independent of experienced traffic load (or interference). While, inclusion of experienced traffic load or interference in the metric is beneficial in that routes adapt to local good opportunities and mitigates congested areas, it is not only beneficial and as straightforward as it may look as stability issues could be a problem. Most state of the art routing metrics do not include experienced traffic load and interference due to the stability issue, and therefore the focus here is put on the metric without experienced traffic load and interference.

A metric that minimizes the number of hops has been popular in fixed networks due to its simplicity, and has therefore occasionally been considered for wireless routing such as in many routing protocol proposed within IETF MANET [1]. Such metric can be expected to work poorly in a wireless channel as it, due to its inherent fixed wired network background, do not account for interference among transmissions and that different link rates are often supported in wireless networks. Such hop metric correspond to assigning a unit value to each link, i.e. the cost from node $v_i$ to $v_j$ is

$$\Delta C_{ij} = 1$$

(2a)

Yet another link metric example is to use the average inverse link rate [10] (or throughput) assuming rate adaptation capabilities. The benefit of this metric is that it strives to offer the least time resource utilization (or delay) along a path. This metric result in a link cost according to

$$\Delta C_{ij} = \frac{1}{\bar{R}_{ij}}$$

(2b)

Where $\bar{R}_{ij}$ is the average link rate (or throughput) between node $v_i$ to $v_j$. This rate can be estimated through knowledge of path gain, transmit power, receiver noise level and available modulation and coding schemes, or over time based on how well communication works for instance in presence of unpredictable interference. Typically for this metric, transmit powers are assumed fixed or slowly controlled.

Other metrics, that will not be elaborated in greater detail here are for instance the physical distance between to nodes, the inverse of the average path loss [11], the link associativity or reliability [12]. Note that the path loss metric is equivalent to minimum power routing, provided one strives to achieve a predetermined signal to noise level at the receiver and power control is permitted. Other metrics account for interference in various respects such as in Least Interference Routing (LIR) where the idea is to use a route that causes least destructive interference. Another interference considerate metric is in Least Resistance Routing (LRR) where the idea is to use a route encountering the least interference. Both LRR and LIR are presented in [11]. A range of other metrics are also surveyed in [13] and in [14].
III. ROUTING METRIC AND IMPLEMENTATION

A. Routing metrics

A salient characteristic of floor acquisition oriented medium access schemes is that nodes may be blocked when other nodes are transmitting or receiving. It could therefore be argued that it would be beneficial if traffic flows were routed over paths were the number of blocked nodes was minimized. In this way, as fewer nodes would be blocked when sending data along a route, those nodes could forward their own or other nodes traffic instead. In the following, it is assumed that RTS and CTS messages are short relative to data transmissions, and the routing metric can be opted for the latter.

The core idea proposed here is to determine the joint set of number of blocked stations for each link, i.e. the number of nodes being blocked by both the sender and the receiver (including the sender and the receiver\(^5\)), and use this figure as part of the link cost.

Two variants of link cost metrics are suggested, one with only the number of blocked nodes, and another one with the number of blocked nodes times the expected transmission duration. More formally, the two variants of link metrics between \(v_i\) and \(v_j\) are defined as

\[
\Delta C_{ij} = |N_i \cup N_j| \quad \text{and} \quad (2c)
\]

\[
\Delta C_{ij} = |N_i \cup N_j|/R_{ij} \quad \text{and} \quad (2d)
\]

where \(N_i\) and \(N_j\) are the sets of nodes that are blocked by the transmitter and the receiver, respectively, i.e. when communication potentially occur, and \(|\cdot|\) is the cardinality of the set (i.e. the number of elements comprised in the set). \(R_{ij}\) is the expected link rate (or throughput) that is supported between node \(v_i\) and node \(v_j\). Note that the sender is included in the set \(N_i\), and the receiver is included in the set \(N_j\). The method to determine and signalling link rate (or throughput) between the nodes is beyond the scope of this paper.

The net result of the metric (2d) is that packets are sent along routes that minimizes the number of blocked stations along the route. By considering the expected communication duration with the number of expected blocked nodes, as in (2c), the metric helps finding a path that concurrently avoids long time blocking exposures as well as striving to minimize the number of blocked nodes, (read, good for system capacity). Apart from offering a heuristically good path, i.e. with few hops and low transmit time consumption, the incorporation of transmit time further strive to yield a heuristically near minimum delay path.

B. Distributed implementation

While the metric may be used both for centralized, decentralized and distributed operation, the latter will be considered here. Since shortest path routing is known to be possible to implement with the distributed Bellman-Ford algorithm, see section II, and topology control can also be executed in a distributed manner, the focus in the following is how to determine the number of blocked nodes per link, i.e. the new aspect introduced by the proposed metric. Two examples will be given on how to estimate the number of blocked nodes for a sender and receiver node pair.

In the first example, as part of the overall routing scheme, a function in a first node determines a list comprising the set of nodes that will be blocked by the first node. This list (of identities, e.g. unique MAC addresses as used as identifiers in IEEE 802.11, or the temporary identifiers AID for power saving in IEEE 802.11) is then disseminated to the surrounding nodes (e.g. as part of the beacon frame in IEEE 802.11 or as a self-contained routing information message sent as a regular data packet). A second node overhearing this message determines the union of the list of the first node and its own corresponding list, and then the cardinality of resulting set.

In the second example, a first node overhears any messages sent to and from another second node and monitors the sender and receiver address fields. In this manner, the first node can determine the set of nodes that may be blocked by the other second node when communicating. Then, the first node determines the union and then the cardinality of first node and the second node sets of potentially blocked nodes. The procedure is repeated and continuously updated for all neighbour nodes in both examples above.

Based on the collected information of blocked nodes according to the first or the second example operation, the link costs based on metric (2c) or (2d) can be calculated and used when determining the shortest paths.

IV. PERFORMANCE EVALUATION

In this section, the performance of the proposed metrics in (2c) and (2d) are assessed and compared with two reference metrics (2a) and (2b), where the latter two corresponds to hop and inverse rate metrics.

Clearly, the main interest in this section is to assess the performance differences between the different metrics when forwarding traffic over the determined routes. While the performance could be evaluated directly through forwarding data in a network with the routes, the result would then not just be dependent on the calculated shortest path trees and the medium access scheme, but also depend on other aspects such as congestion control and traffic models used for the evaluation. Another, but more indirect, method is to avoid simulating the actual forwarding of data and simply assessing

\(^5\) An alternative is to only consider the directly blocked nodes, and exclude the senders and receivers from the blocked sets.
the characteristics of the shortest path trees themselves. While
this indirect method does not perfectly model the actual
performance experienced at forwarding, it should be seen as a
first evaluation attempt while it also believed to be a fairly
good indicator of the relative merits of the different metrics.

The scenario that is evaluated is a 15·15-node square grid
network. With 225 nodes, 225 shortest path trees are spanned
where each node serves as a root. This means that each user
can communicate with any other node in the network through a
route comprising one or more hops. Shortest path trees are
determined by using the metrics (2a)-(2d). Based on the
resulting trees, two types of measure of the trees goodness are
studied for all four metrics and two other goodness measures
are used for (2a) and (2c) only.

For the first performance measure applying to the four
metrics, the blocking duration times the number of blocked
nodes is summed up for each link along a route. Note that this
performance measure is of the same kind as the metric in (2d)
and hence could be argued to act as a circular proof of
optimality of the metric in (2d). Yet, seeing it from the other
direction and accepting that this performance measure is a
useful measure in the first place, it follows that a routing metric
that targets optimization with respect to the performance
parameter is merely a natural consequence of a wise choice of
the performance measure as such. For the second performance
parameter, the duration that a node is blocked by other routes
or the own route is summed up. At closer scrutiny, the metrics
in (2a) and (2c) do not involve any rates and may hence be
used for systems supporting only one rate. Those two metrics
are also evaluated with two other performance measures. The
first of those two determines the blocking instances times the
number of blocked nodes, which is then summed up for each
link along a route. The second calculates the instances that a
node is blocked by other routes or the own route, which is then
summed up. The performance measures are, as will be seen
later, plotted as complementary Distribution Functions (CDFs)

Several assumptions are needed to make the evaluation
approach with shortest path tree simulations valid, such as
assuming the use of identical packet sizes as well as identical
traffic loads between all nodes. Further evaluation assumptions
are identical node transmit powers, a power law loss channel
model with a propagation constant of $\alpha = 3$, and that the link
rates are determined based on the interference free Shannon
rate of the link. The interference free assumption is clearly an
oversimplification, but can be motivated in part with that
interferers are never contained within the regions of blocked
nodes. It is also a matter of how efficient the MAC protocol is
to pack, i.e. reuse, the medium with concurrent transmissions.
Finally, fairly high value of the propagation constant reduces
the interference quickly with increasing distance.

The performance is evaluated for two different blocking
ranges, $r_1$ and $r_2$, where the range is defined as the distance
where the spectrum efficiency is $6/20 = 0.3$ b/Hz/s (this is the
equivalent spectrum efficiency for IEEE 802.11a for its lowest
rate 6Mbps over 20 MHz bandwidth for which the virtual
carrier sense flag is set). The blocking ranges is set by the
transmit power to be equivalent to just barely reach the closest
node ($r_1$) as well as three times that distance ($r_2$).

Fig. 3 shows eight CDFs for the first performance measure,
i.e. the sum of the blocking duration times the number of

![Figure 3. CDFs for per route performance with metric (2a)-(2d)](image)

![Figure 4. CDFs for per node performance with metric (2a)-(2d)](image)

![Figure 5. CDFs for per route performance with metric (2a), (2c)](image)

![Figure 6. CDFs for per node performance with metric (2a), (2c)](image)
blocked nodes for each link along a route. Two transmit ranges in combination with four routing metrics are shown. It is found that at small blocking ranges, just barely reaching the closest neighbours, the performance is more or less identical for all four routing metrics. When the larger blocking range is considered, it is noted that the performance where the number of blocked nodes is considered, (2c) and (2d), offers an improvement compared to their counterparts, (2a) and (2b), which omits blocked node information in the metric. Moreover, the metrics involving the inverse rate, (2b) and (2d), performs significantly better than the metrics, (2a) and (2c), without any rate dependency.

In Fig. 4, eight CDFs for four different metrics and two transmit ranges are shown that represents the total duration a node is blocked. It is noted that the proposed metrics in (2c) and (2d) offer a lower variance than the metrics (2a) and (2b) for both the shorter and longer blocking range. This is so since the metrics in (2a) and (2b) causes a majority of routes to go through the centre of the network, hence causing a large load of the nodes in the networks centre. In contrast, the metrics (2c) and (2d) tend to take paths at the outskirt of the network as fewer nodes are blocked at the network boarder. One can also see that the mean load, in terms of blocking duration is reduced when the larger transmit range is used in combination with metrics involving inverse rates.

Fig. 5 shows four CDFs for the third performance measure, i.e. the sum of the blocking instances times the number of blocked nodes for each link along a route. This performance measure is only applicable to the non-rate dependent metrics (2a) and (2c). It is noted that the metric (2c) is slightly better than (2a). With increasing transmit range, the performance decreases for both (2a) and (2c).

In Fig. 6, four CDFs representing the total number of instances a node is blocked by other nodes communications or its own is shown. Also here is the variance lower for the metric (2c) compared to (2a). Moreover, it is noted that an increased transmit range result in degraded mean performance for both metrics.

In all, the simulation results are interpreted that if possible one should include the number of blocked nodes in the routing metric, or include the inverse rate in the routing metric, or preferably include both aspects in the metric.

V. CONCLUSIONS

This paper considered a routing metric specially crafted for floor acquisition oriented medium access like schemes such as IEEE 802.11 DCF. The core idea was to include a measure of the joint set of blocked nodes at both the sender and the receiver, as part of the link cost. The metric strived to minimize the accumulated number of blocked stations, or in an alternative metric the sum of number of blocked station times the blocking duration, along a routing path. The idea was to free up nodes that are blocked in the state of the art routing metrics and to enable those to be engaged in forwarding other traffic, thus increasing the network capacity. Shortest path tree generation with the proposed metrics and two references metrics, hop and inverse rate, revealed that accounting for blocking in the routing metric appears to have the potential to increase the throughput and reduce the traffic load variance among the nodes.

REFERENCES