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RARE – Resource Aware Routing for mEsh

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***Abstract*— An important element of any routing protocol used for Wireless Mesh Networks (WMNs) is the link cost function used to represent the radio link characteristic. The majority of the routing protocols for WMNs attempt to accurately characterise the radio link quality by constructing the link cost function from the measurements obtained using active probing techniques, which introduces overhead. In this paper we propose a new approach called Resource Aware Routing for mEsh (RARE) which instead employs passive monitoring to gather radio link information. This results in a smaller overhead than the other methods that require active network probing, and is load independent since it does not require an access to the medium. Moreover, we show that our RARE approach performs well in a real radio environment through a number of experiments performed on a static 17 node WLAN mesh testbed.**

I. Introduction

Wireless Mesh Networks (WMNs) [1] are a type of radio-based network system which require minimal configuration and infrastructure. This technology allows for quick and inexpensive deployment of wireless local area networks (WLANs). The typical wired LAN is configured using static routes. However, the dynamics of the radio environment require the use of routing protocols which can dynamically adapt their routes according to changes in the network environment. WMNs can change in the following ways:

- their link characteristics change – this is because of external sources of interference; moving nodes and obstacles; and interference from other nodes.
- their topology changes – this is because changes in the link characteristic may result in the loss of connectivity, changing the whole topology of the network.

The choice of radio technology for WMNs influences the performance of the network. Consequently, the routing protocol needs to be aware of this and cannot operate in the same way as wired networks which are often agnostic about the underlying communication medium. Researchers have proposed a variety of new routing protocols developed specifically for ad-hoc wireless mesh networks which are often tailored to meet requirements of the radio or the application for the mesh technology.

Any routing protocol which aims to find stable and high throughput paths for demanding users must be aware of the underlying radio and needs to accurately represent it using an appropriate link cost function. Also due to the dynamics of the wireless network, the nodes need to be capable of tolerating imprecise state information. To deal with the dynamics and hence inaccuracy of the routing information, routing protocols adapt to changes in a proactive (OLSR [2] or HLSL [3]) or reactive (DSR [4] or AODV [5]) manner. However, the subject of how efficiently these protocols maintain routing information and adapt to its changes is outside of scope of this paper.

In this paper we focus on the way the radio link characteristics are represented by the link cost function. There are various ways in which such a mapping can be performed (an evaluation of the performance of routing protocols with different metrics is presented in [6]). The route computation methods usually select least-cost paths between the source and the destination, where the cost of the path is defined as the sum of the costs of all links along the path. The link cost function can be constructed in many ways, so that algorithms can compute minimum hop paths, maximum bandwidth paths, minimum loss paths, minimum delay paths, etc. Thus the link cost function allows one to optimise the utilisation of the wireless medium, adapt to changes in wireless environment, minimise contention between data flows, select stable high throughput paths with low associated delays. However, it is often difficult to meet conflicting goals simultaneously in highly dynamic wireless environments.

In this paper we propose a novel method for creation of a link cost function – Resource Aware Routing for mEsh (RARE) which is based on passive monitoring of the wireless medium. We show that by using passive monitoring we can create a sufficiently accurate link representation that will allow a routing protocol to select high throughput and high quality paths. The main benefit of our approach is that it eliminates the overhead associated with probing the network used by such metrics as Expected Transmission Count (ETX) [7], Expected Transmission Time (ETT) [8], or Weighted Cumulative Expected Transmission Time (WCETT) [9].

II. Radio Link Cost Function

The link cost function is not restricted to optimising just a single performance metric, it may be used to optimise a number of performance metrics including delay, packet loss, and bandwidth. In our approach we have selected three metrics which we consider as important for WMN performance: signal strength, interference, and bandwidth.

Signal strength — By selecting paths with strong signal we aim to select paths which can support high-data rates with small error rates. However, the delivery probability vs signal strength may depend on the particular receiver (as demonstrated by the diagrams in [10]). Therefore, researchers often prefer to actively measure the delivery rate of the link instead of its signal strength [7], [9], [11]. In practise such an approach requires each node to broadcast link probe packets, calculate how many of these probe packets it has received, and feedback the results of such calculations to other nodes. This however generates measurement overhead. Our approach is to use the received signal strength indicator (RSSI), which the IEEE 802.11 proposes to report the RF energy level. Even though it does not reflect the delivery probability as well as the actively measured values there is still a good correlation between delivery probability and signal strength [12].

Interference — Interference has been identified as a key cause of performance degradation in WMNs [13], [14]. Thus, researchers have proposed to actively measure it by checking how activity on one link influences the throughput on other links [14]. However, this procedure for a network with n nodes requires the testing of n^4 pairs of nodes (or n^2 when simplified procedure is employed) while other nodes need to remain idle. Such procedure is time consuming and difficult to realise on a live network. Therefore, we propose a simpler method which estimates average contention instead of interference. To measure this we put the wireless card into the RFMON (Radio Frequency Monitoring) mode and monitor when multiple stations are contending for access and as such we can obtain the average level of contention.

Bandwidth — The amount of bandwidth available for the data transfers is also an important factor. Draves et al. [9] have proposed measuring it using the technique described in [15]. This is based on sending both small and large probe packets whereby the bandwidth is estimated by dividing the size of the large probe by the time difference between the receipt of the small and the large probe packets. Bicket et al. [8] simplified this procedure which reduces the measurement overhead by using broadcast packets instead. We propose to estimate the available bandwidth by passively monitoring the activities of the nodes, the rates used for data transmission, and the packet sizes used.

Thus the methods which we propose for obtaining the signal strength, interference and bandwidth estimates are non intrusive and do not generate a measurement overhead. These methods are based on passive monitoring which allows a wireless node to intercept the transmission activities of other radios within its communication range. The passive monitoring and statistical analysis of available bandwidth, average contention (amongst other metrics) is performed by a WLAN Resource Monitor [16] application developed at our laboratory. The use of all three elements signal strength, interference, and bandwidth diversifies the path selection criteria and instead of optimising just one of the performance metrics, provides a trade-off which potentially can offer fairer access to the medium.

There is however another problem which passive monitoring alone cannot resolve and this relates to link asymmetry.

III. Link asymmetry

Researchers have observed [17] that wireless links often exhibit quite different propagation conditions in one direction than in the other. Broadcast packets may be successfully sent from node to another but not in the opposite direction. This is known as link asymmetry.

The links in our static 17 node indoor WLAN mesh network also exhibit this link asymmetry. We demonstrate this by using the signal-strength symmetry (SSS) parameter first defined in [17]. The $SSS(i,j)$ is defined as the minimum of the ratio of the forward to the reverse signal strength or vice versa.

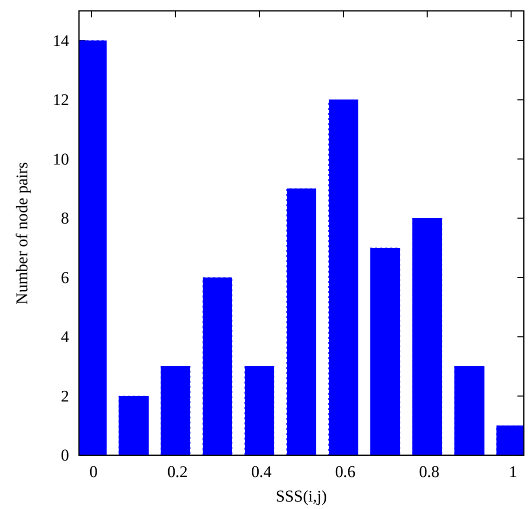


Fig. 1. A histogram of signal-strength symmetry (SSS)

Figure 1 shows the SSS distribution measured on our static 17 node indoor WLAN mesh network where the signal strength values were collected over a 24 hour period. This diagram demonstrates that in our mesh network most links were asymmetric. Only one link was perfectly symmetric ($SSS = 1$), 14 links were completely asymmetric($SSS = 0$), and most links exhibiting significant asymmetry ($SSS < 0.7$). Furthermore, from Figure 2, it can be observed that there is no correlation between the forward and reverse signal strengths. Therefore, this lack of correlation suggests that a successful broadcast of a packet from one node to another does not imply successful transmission in the opposite direction.

The routing protocols for IEEE 802.11 WLAN mesh networks need to be aware of this link asymmetry. This is because HELLO messages which are exchanged between nodes to discover their neighbours are transmitted as broadcast messages without acknowledgements. As such, they may get through to recipients by utilising highly asymmetric links. Data frames on the other hand require acknowledgements which require bidirectional communication links. This creates the possibility that links which cannot be used to transfer data frames may be erroneously defined as valid links in the routing table.

One of the methods described in [18] for dealing with link asymmetry is link hand-shaking. This method extends

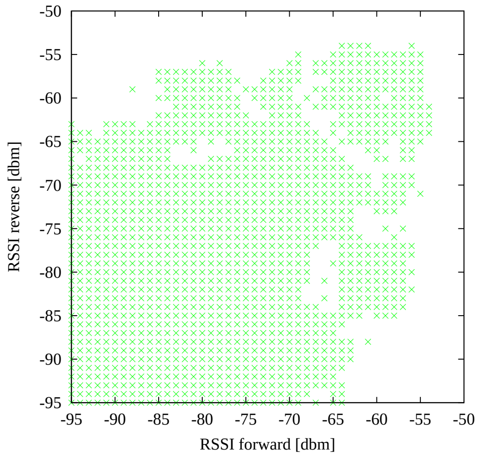


Fig. 2. The correlation of forward and reverse signal strength

HELLO messages so they include a nodes neighbour set. Such modification of HELLO messages allows the other nodes to detect if the link is bidirectional or not. Therefore, by using the method of hand shaking the routing protocol can detect if the link can be used for data transfers and can therefore incorporate the link into the routing table.

IV. RARE

The Resource Aware Routing for mEsh (RARE) is a routing module which aims to make a routing protocol aware of the wireless resources. The implementation described here uses DSR [4] which is combined with a link cost function which was specifically developed for this purpose. The RARE module obtains the information about the wireless medium through passive monitoring. It measures the three elements which we have have been recognised as significantly influencing the performance of wireless mesh networks, namely the signal strength, contention, and available bandwidth. The three elements are used to construct the radio-aware link cost function. RARE also employs extended HELLO messages (as suggested in [18]) to counteract the link asymmetry, however, we further extend them to include information about the signal strength. This allows RARE to detect how strong the radio signal is in both directions and consequently to determine if the link can be used for data transmissions.

The RARE link cost function involves three parts comprising bandwidth, contention, and signal strength measurements. The form of the link cost function formula is as follows:

$$Link\_Cost = \alpha \frac{C - BW_a}{BW_a} + \beta \frac{RSSI_{max} - RSSI}{RSSI} + \gamma * N_c \qquad (1)$$

where:

BW_a	is the available bandwidth
C	is the link capacity
$RSSI$	is the signal strength (RSSI) value
$RSSI_{max}$	is the maximum signal strength (RSSI) value
N_c	is the average contention
α,β,γ	are the weights associated with the bandwidth, RSSI and contention components

The formula for the bandwidth component is the same as that used in ARPANET [19] network. Also for the signal strength component we have used the same formula. This is because we want to use it in a similar way to the available bandwidth, namely when its value reaches a minimum the traffic needs to be redirected from the link. Unfortunately, a link cost function which attempts to adapt to traffic changes and signal strength changes can exhibit instability [19]. Traffic oscillations are most likely to occur when the costs of different paths vary widely. The paths which have a lower cost may attract the majority of the incoming traffic and become congested while the paths which reported a high cost may become idle.

In a wireless environment the values of available bandwidth, signal strength, and contention tend to be very dynamic. Therefore, instead of using their current values we smooth the data using an exponential weighted moving average filter which reduces the probability of traffic oscillations, improves reliability, and leads to the selection of more stable paths.

The RSSI value used by the RARE link cost is in fact the minimum value of the two: forward and reverse signal strength.

In Figure 3 we show an example of the RARE link cost function for a link with a contention value of 4 (this means that in order to gain access to this link, on average the station needs to compete with 4 other stations) and the weights specified as follows: $\alpha = 1$, $\beta = 1$, and $\gamma = 10$. Through the weights

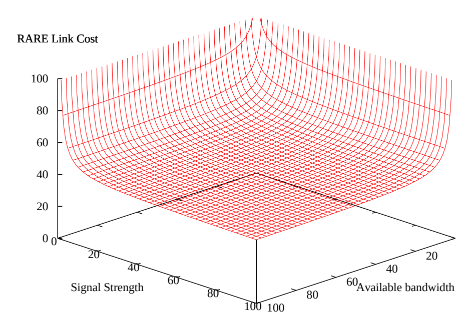


Fig. 3. Example of the RARE link cost function

α,β,γ we can specify the relative importance of the different link cost components.

V. TESTBED

To evaluate RARE we have constructed a testbed which consists of 17 static nodes located indoors on the four floors of the FOCAS[1] building. The building consists of rooms with solid walls and thick concrete floors and solid doors which may be responsible for the high link asymmetries observed in Figure 1.

Each node consists of a Sokeris net4521 board with 133MHz processor and 64MB of SDRAM, and equipped with standard Netgear 802.11a/b/g WLAN cards with Atheros chipsets. All the nodes are running Pebble Linux OS with Madwifi drivers. The implementation of DSR routing protocol comes from the Roofnet project and it is implemented using the Click Modular Router Software [20]. The WLAN Resource Monitor [16] runs as a separate module.

We have set all the WLAN cards to operate in the 802.11g mode. However, on all three channels 1, 6, and 11 there were additional access points operating within the building which were beyond our control, thus we could not completely eliminate all external sources of interference.

VI. RESULTS

In this section we compare RARE with the Estimated Transmission Time (ETT) [8] metric. ETT estimates time required for successful transmission of a frame (including retransmissions) based on the actively measured delivery rate and throughput.

Under the assumption that most users are likely to require network access, in our experiments all of the nodes communicate with the gateway node which is located on the ground floor of our building.

The weights for the RARE were obtained heuristically and after preliminary testing we have specified them as follows: $\alpha = 1$, $\beta = 1$, and $\gamma = 10$.

In this experiment each of the 16 nodes (the seventeenth node is the gateway node) transmits a data stream of identical characteristics to the gateway node. The flow comprises CBR UDP traffic with a packet size of 1470 bytes. Each node transmits a flow with the duration uniformly distributed between 30 second and 10 minutes and then backs off for a period of time uniformly distributed between 30 seconds and 30 minutes. We only modify the intervals between concurrent packets to obtain flows of rates: 64kbps, 128kbs and 256kbps. The results for each of the settings were collected over a 24 hour period and each experiment was repeated to ensure that results can be replicated. Moreover, the tests were performed only during working days, to ensure similar propagation conditions.

In Figure 4 one can observe the throughput obtained by individual flows when RARE and ETT were used. In the cases of three different sending rates, there was little difference between the RARE and ETT performance. As show in Table I, the average throughput obtained for RARE and ETT was almost identical in all cases.

[1] http://www.focas.dit.ie/

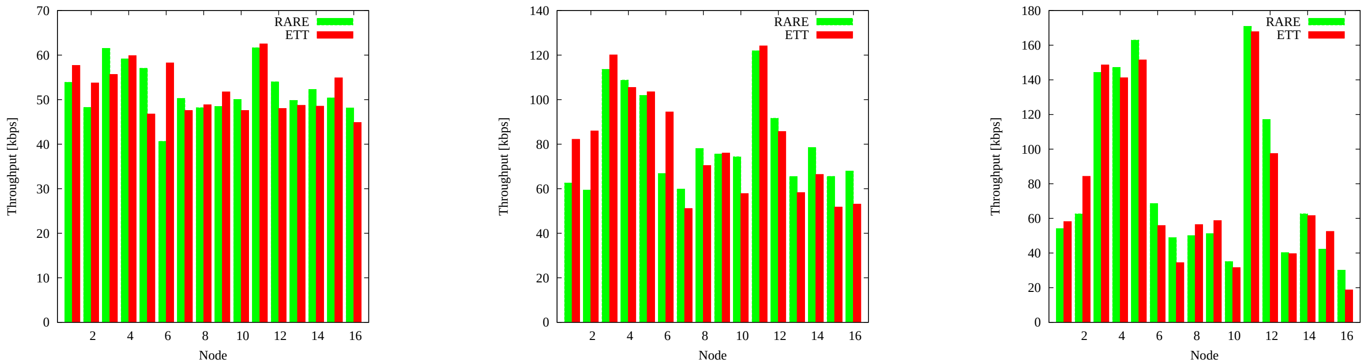
TABLE I
AVERAGE FLOW THROUGHPUT

sending rate	average throughput	
	RARE	ETT
64 kbps	52.1 kbps	52.3 kbps
128 kbps	80.7 kbps	80.4 kbps
256 kbps	80.2 kbps	78.8 kbps

Even though the ETT performs path selection based on delivery rate and the measured bandwidth, and RARE makes routing decisions based on signal strength, available bandwidth and contention, both enable for selection of high quality paths. Both perform the routing task well by assigning a high cost to links supporting only small bit rates and exhibiting high error rates. The marginal differences in ETT and RARE performance shown in Figure 4 may be attributed to differences in propagation conditions, since we could not run both routing approaches simultaneously and we could not isolate the whole mesh testbed.

Figure 4 also shows another phenomenon. It demonstrates that when we increase the sending rate, only the nodes which are the closest to the destination (namely nodes 11, 3, 4, 5 and 12) experience an increased throughput, while the throughput of other nodesis reduced. In consequence, the average throughput does not increase when we increase the sending rate from 128 kbps to 256 kbps (this is shown in Table I). Thus the nodes which are few hops away from the gateway suffer, and so we observe unfairness. The extreme case of such unfairness occurs when instead of UDP traffic we introduce TCP, as shown in Figure 5. The flows which are closest to the gateway (namely nodes 11, 4, 5 and 12) win almost all transmission opportunities, and consume all the bandwidth at the edge of the mesh around the gateway node.

This demonstrates the fact that in wireless mesh networks only well behaved nodes allow fair access to the medium. For example, when the nodes use the network infrequently, this gives the other nodes enough time to access the medium. Moreover, the observed throughput reduction also supports the argument that nodes located a few (frequently cited as four or more) hops away from the destination may experience difficulties in accessing the network. This is because: (i) the data packets at each hop need to compete for access to the medium with the data packets belonging to the same data flow at other hops; (ii) activities of the nodes which are close to the destination reduce the throughput furthermore; (iii) the hidden terminal problem is likely to occur at each hop, thus it is much more severe on a few hops than on a single hop. Consequently, a mesh network which comprises many nodes located four or more hops away from the gateway may only allow fair access to the wireless medium if the nodes use the network infrequently, otherwise extreme unfairness may be observed as shown in Figure 5.



(a) sending rate: 64kbps (b) sending rate: 128kbps (c) sending rate: 256kbps

Fig. 4. Throughput obtained by TCP flows

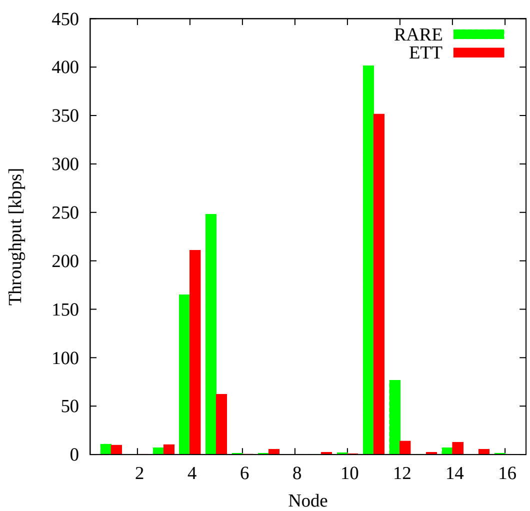


Fig. 5. Throughput obtained by TCP flows

In summary our experiments have shown that RARE can obtain results that are comparable with ETT and because it uses passive monitoring it eliminates the measurement overhead. Moreover, with active probing techniques the probe packets needs to access the medium which may be difficult if the links are congested. Thus routing metrics which obtain radio links characteristics using probing techniques, such as ETT, are load dependent which can introduce an error into path selection process.

VII. Conclusions

In this paper we have introduced a novel routing module which we call Resource Aware Routing for mEsh (RARE) and which combines passive measurements of bandwidth, contention, and signal strength in the calculation of the link cost function. Other metrics such as ETT are based on probing technique involves broadcasting probe packets across the network in order to establish the quality of the communication links. The main drawback of an active technique is that it introduces additional network overhead and moreover its effectiveness is load dependent. The approach which we have used in the RARE is based on passive monitoring which eliminates the need to introduce additional traffic onto the network, is load independent, and can provide additional measures regarding the quality of the link without an associated measurements penalty. We have compared the performance of our RARE module with that of ETT on our experimental 17 node static mesh network. Our results show that the RARE technique has a performance comparable with that of ETT but without the associated overhead penalty.

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