

Interference-aware Multipath Selection for Reliable Routing in Wireless Mesh Networks

Jack W. Tsai and Tim Moors

University of New South Wales, Sydney, Australia/NICTA, Australia
jack.tsai@nicta.com.au moors@ieee.org

Abstract

This paper investigates the problem of selecting multiple routing paths to provide better reliability in multi-radio, multi-channel mesh networks with stationary nodes. Providing reliability is difficult in wireless networks because of unreliable transmissions. Previous work has investigated the use of additional data redundancy to improve the packet delivery rate, but requires node-disjoint paths to be used. In this paper we investigate multipath routing with packet duplication and non-disjoint paths for achieving better reliability and low delay. We propose a path weight function based on the ETT metric and interference minimization. Our solution provides higher packet delivery ratio and lower end-to-end delay when compared to the single path WCETT metric, a maximally disjoint path selection metric, and the CAM metric.

1 Introduction

Wireless mesh networks have gained considerable attention as an alternative solution to applications such as community networks, enterprise networks, last mile access networks to the Internet, etc [1]. Some wireless mesh networks are static and consist entirely of stationary mesh nodes using mains power. Unlike ad hoc networks, which are formed by collections of mobile nodes without the support of fixed infrastructure, static mesh networks have neither mobility or power consumption issues, and so can use different strategies to optimise routing. In this paper, we focus on improving the reliability of data delivery in static mesh networks. Our contribution will benefit applications that require reliability over throughput, such as vehicular traffic control or factory automation.

We define our target network as follows: it is situated in a public area, and uses an unlicensed frequency

band. Consequently, the links are susceptible to different types of interference and fading conditions. Firstly, other devices nearby using the same wireless standard could create contention or interfere with nodes in the network. Devices using other standards within the same frequency band may also interfere. Lastly, changes in the environment, such as vehicular movement or varying weather conditions, may degrade wireless transmission. Because of such inherent unreliability, providing high reliability over a single path may be difficult. One solution to this problem is to use multiple paths to deliver data. Sending redundant data over multiple paths has been proposed as a solution for improving the end-to-end reliability [2, 3].

Multipath routing has been investigated in wired networks [4] for achieving load-balancing and routing resilience. In wireless ad-hoc networks, various multipath routing solutions have been proposed to reduce the route rediscovery overhead and delay caused by topology changes due to mobility, by using backup paths [5, 6]. In our work, we focus on the *concurrent* use of multiple paths. More specifically, we send copies of data over different paths as a means to improve the end-to-end reliability [2, 3].

Some wireless networks reduce interference by equipping nodes with multiple radios that can operate on different channels for different neighbouring links [7]. The multiplicity of radios and channels can also increase capacity, compensating for the load created by multiple copies of data. In addition, each node is able to transmit and receive concurrently, rather than having to wait until a packet has been relayed downstream outside of its interference range. As wireless mesh nodes have more relaxed size and energy consumption requirements than those in ad-hoc or sensor networks, the multi-radio, multi-channel setup provides an effective way of efficiently using the available spectrum.

In a wireless multi-hop network, there is often one, or at most few, paths that are most reliable. If multiple paths are to be used concurrently, then other less reliable paths need to also be used. For example, suppose

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all links in a network have the same reliability, then the shortest path will be the most reliable. There may be a few paths that have the same length as the shortest path, and in a wireless multi-hop network they are likely to be close to the shortest path. If only these individually reliable paths are chosen, the resulting traffic flows could have high mutual interference and may be affected by localised interference simultaneously. Therefore there is a trade-off between individual path reliability and the collective multipath quality.

Our goal in this paper is to provide a heuristic for multipath selection that will exploit the frequency diversity offered in a multi-radio, multi-channel network. Specifically, we focus on improving resilience against random link failures by factoring in the interference between multiple paths that could adversely affect redundant data delivery. Whilst the 802.11 link layer retransmission technique offers a reasonable protection against random losses, it could increase delay. This problem is exacerbated over multiple hops, in which case the resulting delay may be unacceptable for real-time applications. Therefore we also study the ability of multipath routing to provide lower delay than pure retransmission for a given level of reliability.

The rest of the paper is organised as follows. In Section 2 we present background knowledge about existing path selection metrics. Next we present our path selection metric in Section 3. The simulation results are presented in Section 4. Possible future work is discussed in Section 5, and we conclude our work in Section 6.

2 Background

We first present several path quality metrics motivated by high throughput routing in either single or multi-radio networks. We then discuss on the suitability of these metrics at providing reliability in a multi-channel, multi-radio network.

2.1 Expected transmission count and time

The expected transmission count (ETX) [8] metric was proposed to maximise high throughput. It measures the deliverability of broadcast traffic to determine the probability of successfully acknowledged delivery across a link, and the ETX is the reciprocal of that probability.

The expected transmission time (ETT) [9] builds on ETX but also considers the difference in link bandwidths: $ETT = ETX * S/B$, where S denotes the packet size, and B denotes the link bandwidth. ETT alone cannot adapt paths in response to mutual-interference of multipath traffic because any single flow will hardly affect the ETT.

2.2 Weighted Cumulated ETT (WCETT)

WCETT [9] was designed for use in multi-radio networks. It considers the fact that links may operate at k different orthogonal channels, thus higher throughputs can be achieved by exploiting channel diversity. The WCETT for a path is:

$$WCETT = (1 - \beta_W) * \sum_{i=1}^n ETT_i + \beta_W * \max_{1 \leq j \leq k} X_j, \quad (1)$$

where $\sum_{i=1}^n ETT_i$ accounts for the ETT values of all links along the path of an n -hop path. $\max_{1 \leq j \leq k} X_j$ is the sum of ETTs of the links on the *bottleneck* channel, the channel on which the combined link ETT is the greatest. The rationale behind the bottleneck channel ETT is that the time spent during data transmission on this particular channel is effectively restricting the throughput of the whole path, therefore a path with lower bottleneck ETT will yield a better throughput.

2.3 Channel Aware Multipath (CAM)

The CAM [10] metric extends WCETT to support multipath routing. The original WCETT metric is included in the calculation of the *independent path quality index* (γ), which is a weighted-sum of WCETT values of individual paths based on each path's traffic utilisation ratio. In addition to the individual path quality captured by WCETT, CAM introduces another component in the metric to capture the interference among common channel links on different paths. For every channel, the ETT of all the links in the paths that is on the channel is summed. The maximum of these sums is the *inter-path interference index* (λ), which essentially extends the bottleneck channel time concept to multiple paths.

$$CAM = \beta_{CAM} * \lambda + (1 - \beta_{CAM}) * \gamma, \quad (2)$$

2.4 Discussion

CAM has been designed to maximise channel diversity amongst selected paths. Whilst this may be desirable in reducing interference, spatial diversity is not considered. Why is spatial diversity important? Consider the two types of interference illustrated in Fig. 1. In Fig. 1(a), the transmission from the black node A on one path causes *inter-path interference* at node B on the other path. This type of interference will affect the end-to-end delay but will not have a great impact on reliability unless the interference starts to cause excess delay and packets being dropped from interface queues. In Fig. 1(b), nodes on both paths are being affected by an external interference source. In this case all the paths within the interference range of

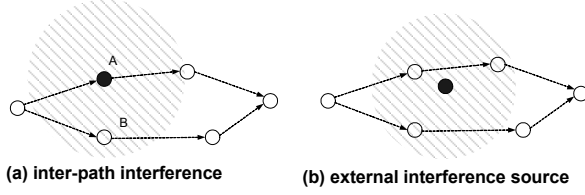


Fig. 1 Type of interference

the external source will not be able to deliver traffic for the duration of the interference.

Both WCETT and CAM also assume that all links using the same channel interfere. This is unrealistic in large networks with spatially separated paths. The authors of CAM proposed using the interference graph of a network to only include links that interfere. However this approach was not implemented and evaluated. Another issue we see with bottleneck channel time is that it is a local metric. It only considers the interference between selected paths but not also the interference to and from other nodes in the network that have not been included in the paths. This approach may be acceptable when the traffic load in the network is light, but as traffic builds up, the channel use from neighbouring links will start to affect transmissions on the selected paths. It is possible that a set of paths with low bottleneck ETT may be surrounded by high load links, while another set with a higher bottleneck ETT experiences less contention from neighbours and is the better choice overall. This scenario is illustrated in Fig. 2.

3 Path selection metric

In this section we present a new interference-aware multipath selection metric. Our selection metric and algorithm aims to minimise interference (between paths and to neighbour nodes), without assuming that interference is global, and considers link quality and the delaying effect of long paths, when selecting paths.

3.1 Path Interference Cost

The path interference cost reflects the degree of interference between links operating on a common channel along the selected paths. To help define the path interference cost, we first define the interference cost for a link (i, j) on channel c in a network N as:

$$LI_{ij}(c, N) = ETT_{ij}(c) * S_{ij}(c, N), \quad (3)$$

where $S_{ij}(c, N)$ denotes the number of nodes in network N that are affected by interference from link (i, j) on channel c . In this work we assume interference to be binary – two nodes either do or do not interfere. This assumption allows us to simplify the computation of metrics. We plan to investigate more accurate classifi-

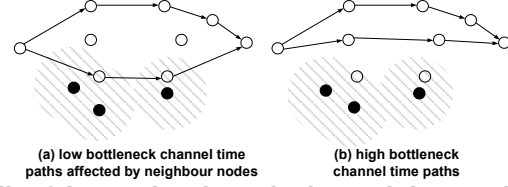


Fig. 2 Lower bottleneck channel time paths affected by neighbour node interference

cations of interference in the future. The path interference cost for a set of paths P is simply the aggregate of all link interference costs along the paths:

$$PIC_P = \sum_{ij \in p} LI_{ij}(c, P) \quad (4)$$

3.2 Neighbour Interference Cost

Similar to the path interference cost, the neighbour interference cost represents the channel time cost to nodes close to the paths, and it is defined as:

$$NIC_P = \sum_{ij \in p} LI_{ij}(c, N - P), \quad (5)$$

where the set $N - P$ includes all the nodes in the network not on the paths. Note that in some cases, this cost may be too conservative. Consider the case where some neighbour nodes are close together. NIC incorporates the interference cost to each of these nodes, even though the interference cost from the path to the neighbour nodes may be small compared to that between the neighbours that already exists.

3.3 Weighted Interference Multipath metric

The Weighted Interference Multipath (WIM) metric is a weighted average of path interference and the neighbour interference costs.

$$WIM_P = \beta * NIC_P + (1 - \beta) * PIC_P, \quad (6)$$

where the parameter β satisfies $0 \leq \beta \leq 1$.

The WIM metric can be interpreted as a balance between local and global considerations. The path interference cost component reflects the total channel time along the paths that is consumed when the channels are concurrently used. The smaller it is, the better the paths will be at providing low end-to-end delay, assuming interference to neighbour nodes is negligible. On the other hand, the neighbour interference component favours paths that have less interference to nodes that are not on the paths. This could be beneficial when the network load is high such that interference from neighbouring nodes starts to affect, or even dictate, the traffic on the paths.

4 Simulation

We now present the simulation results and discuss the effectiveness of WIM at selecting paths that provide reliable data delivery and low end-to-end delay. The simulator used is NS2 v2.30. We have modified the link layer component to support multiple radios and multiple non-interfering channels. We use the Optimized Link State Routing (OLSR) protocol [11] to provide the basic link-state exchange framework.

Since our path selection algorithm is based on the full knowledge of available paths and is performed at the source node, we have implemented source routing. Although source routing carries the penalty of additional routing header overheads, it is necessary to facilitate packet duplication on multiple paths – each duplicated packet is assigned a path by the source node. One way to reduce this extra overhead is to set up a flow id [12] for each path and store next-hop information in intermediate hops. This enables hop-by-hop forwarding based on flow ids and removes the need for source route header. In our simulation, we do not implement this flow based routing.

The network topology is generated by placing 100 nodes randomly over a 2km x 2km area. The distance between any two nodes is at least half the transmission range, and every node has at least one neighbour with which it can communicate. The topology is not partitioned. The minimum distance requirement ensures an upper bound on the node density. Each node is equipped with two 802.11b radios tuned to the same pair of orthogonal channels. Unless otherwise stated, we do not use link layer retransmission as it simply maintains high packet delivery ratios at the expense of end-to-end delays, which masks the comparison on path reliabilities. The transmission range and the interference (carrier-sensing) range are 250m and 550m, respectively. The source and destination nodes are chosen randomly. Similar to CAM, an exhaustive search is performed to discover and evaluate multipath routes. The computational complexity of the algorithm is $O(h^{nc})$, where h is the hop-count limit, n is the number of paths, and c is the number of channels used.

To model loss and fading in NS2 we implemented the Gilbert-Elliot loss model. The probabilities of transition from the good state to the bad state and from the bad state to the good state are both 0.1. The good state loss and the bad state loss probabilities are set randomly in the ranges [0, 0.2] and [0.2, 0.4], respectively. The above setting gives us an average loss rate between 0.1 and 0.3. The sojourn time in either state is set to 10ms.

The performance of our multipath algorithm is evaluated against three alternatives – the WCETT single path, a simple maximally disjoint (MD) multipath,

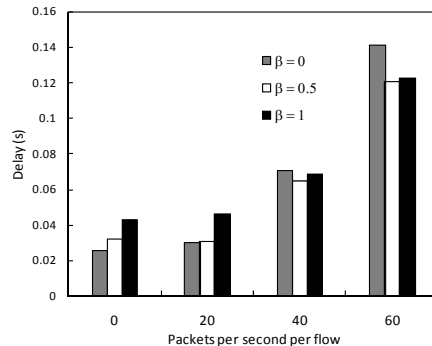


Fig. 3 End-to-end delays as β changes

and CAM. In MD the paths with the fewest shared nodes are selected. We assign both β_W and β_{CAM} to 0.5, as it appears to be the best overall choice in the respective studies of WCETT and CAM.

4.1 Effect of β

We first examine the impact of β on selecting low delay paths. Recall that a small β favours low intra-path interference paths, while a large β favours paths with lower interference to the neighbours. We performed simulations with $\beta = 0, 0.5$ and 1 under various network loads. We simulate network load conditions by establishing CBR traffics with various packet rates. Results in Fig. 3 show that when the traffic is light (i.e. 0 and 20 packets per second CBR), using a β of 0 results in paths with the lowest delay. As network load increases, the interference effect from neighbour nodes starts to dominate, and a larger β works best in selecting low delay paths. The problem of choosing the right value of β depends on the specific network topology at hand and the traffic load in the network at the time of path selection. We plan to investigate on dynamically setting β in our future work. For our simulations in this study we set β to 0.5.

4.2 Path length

We now evaluate the performance of our multipath algorithm as the distance between the source and the destination changes. We use hop-count of the shortest path as an indication of the distance between the source and the destination. The results are presented in Fig. 4. As expected, higher delivery ratios were achieved with sending duplicated packets over two paths. The CAM metric selected paths that provided lower delays but lower delivery ratios, while using WIM, the selected paths provided the highest delivery ratios with slightly higher delays. This is due to the fact that the paths selected using CAM tend to be closer to the shortest path and have fewer hops. Each pair of paths also traverses the same hops but using different channels (see Section

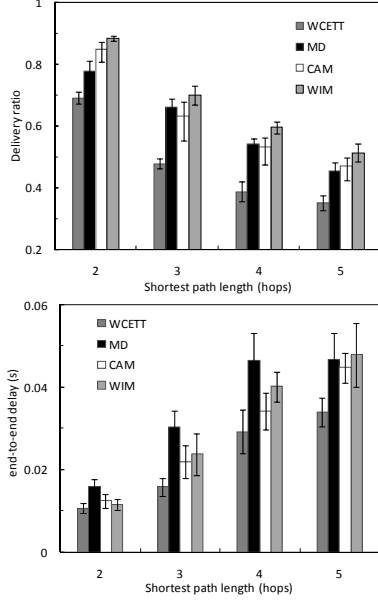


Fig. 4 Routing performance comparison, no link layer retransmissions

4.3). Therefore if a link is experiencing fading (i.e. both channels are in the bad state), then both paths will likely drop packets at the same time, resulting in a higher loss even though the paths are shorter.

4.3 Resilience to Localised Failures

We now examine the degree of spatial diversity of the paths selected, and how this physical separation can provide resilience to localised failures. In Section 2.4 we showed how an external interference source can cause localised failure within an area. We model this type of geographically correlated failure as a circle of radius R , similar to that used in [13]. To compute resilience to localised failures, we randomly place a point and set all the nodes within a radius R of 200m to fail. The resilience is 1 if there are one or more paths that are still available, and 0 if both the paths fail, i.e. if all the paths have nodes within the radius. If the circle covers either the source or the destination, the result is discarded since there is no way to avoid path failure. We first show the average distance between paths in Fig. 5 (a). The distance is calculated by averaging the distances between nodes in one path and the nearest node in the other path. It is easily noticeable that the separation of paths selected using CAM is significantly smaller than that using either of the other metrics. This reflects the use of bottleneck interference in the CAM metric; by not considering interference between every node in the paths, spatial diversity is greatly reduced. Fig. 5(b) shows the resilience values. As expected, spatial diversity is strongly correlated to resilience against localised failures.

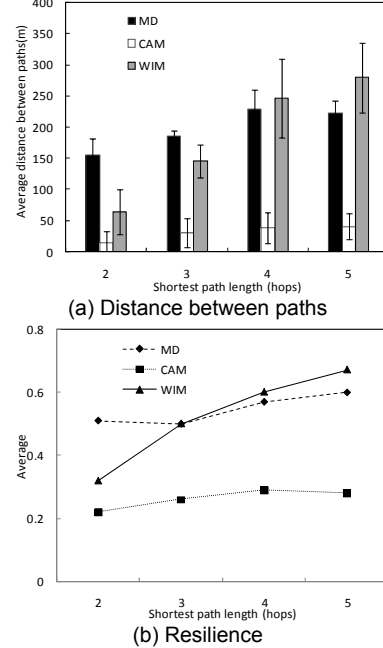


Fig. 5 The impact of spatial diversity on resilience against localised failures

4.4 Link Layer Retransmissions

In Section 4.2 we presented the path performance without the effect of retransmissions. Although using data redundancy over multiple paths yields marked improvement in delivery ratio, the best achievable delivery ratio of 0.91 in our simulation results will not provide adequate reliability in most applications. Here we investigate using various degrees of link layer retransmission to further reduce packet loss.

Fig. 6 compares the path performance as the maximum number of link layer retransmissions, N_r , increases from 0 to 4. Using single path WCETT, an acceptable average delivery ratio of 0.97 is only achieved when 4 retransmissions are allowed. Using two paths with duplicate packets yields significantly higher delivery ratio when N_r is 0 or 1. However, with CAM the delivery ratio actually decreases when N_r is increased from 3 to 4. This is due to the low spatial diversity in the paths selected by CAM. With more retransmissions, the interference between paths starts to cause queue overflows, and when N_r is 4, the benefit of doing more retransmissions at each hop is completely offset by the number of packets dropped due to queue overflows. This is also reflected in the jump in the delay. On the other hand, using WIM, we were able to achieve a delivery ratio of 0.95 and a delay of around 0.15s when N_r is 2. Using three paths, additional reliability can be achieved, though the improve-

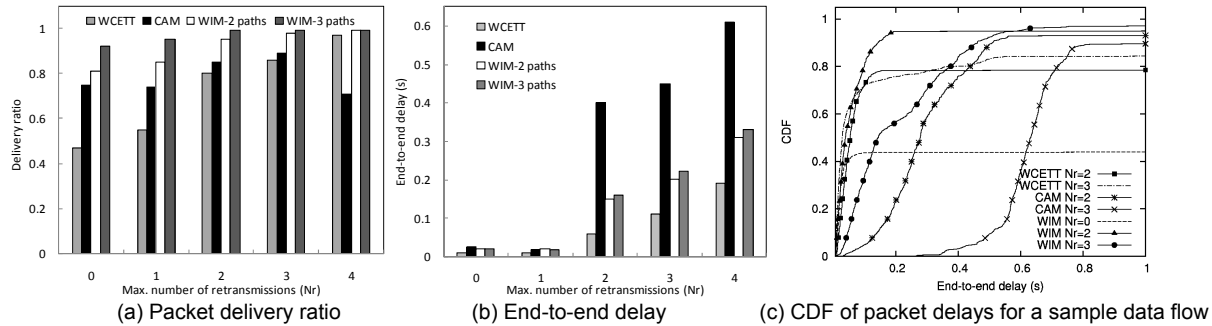


Fig. 6 Routing performance comparison, with link layer retransmissions

ment in delivery ratio is less significant when N_r is greater than 2.

5 Future Work

In this paper we presented an initial evaluation of using multipath routing with interference minimisation for achieving reliability. We expect to follow up a number of issues not addressed in this work. Firstly, we used an exponential exhaustive search to select paths; this may not be feasible in networks with reasonably rich selections of paths or when the number of paths needed increases. Secondly, packet duplication uses the available capacity rather inefficiently; a better way to provide data redundancy is to use erasure code. A method to dynamically evaluate the best value of β to use is also needed. Lastly, the calculation of WIM uses a binary categorisation of interference. A more realistic and accurate method would be to base the degree of interference on the physical distance between nodes.

6 Conclusion

Providing high reliability over a wireless multi-hop network is inherently difficult due to the nature of wireless medium. Sending redundant data over multiple paths provides resilience to random failures. However, interference between data flows on different paths creates contention and affects performance, and the additional traffic reduces the overall network capacity. In this paper we investigated using interference minimisation to provide reliable data delivery. We have proposed the WIM path selection metric which considers both inter-path interference and interference to and from neighbour nodes. We showed that in a multi-radio, multi-channel environment, WIM provides lower delay and higher reliability paths than CAM and a simple maximally disjoint selection algorithm. With unreliable links, WIM is able to achieve a delivery ratio of 0.95 using two paths and two retransmissions.

7 Reference

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