A Review of Multipath Routing Protocols: From Wireless Ad Hoc to Mesh Networks

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Abstract – Multipath routing allows building and use of multiple paths for routing between a source-destination pair. It exploits the resource redundancy and diversity in the underlying network to provide benefits such as fault tolerance, load balancing, bandwidth aggregation, and improvement in QoS metrics such as delay. There are three elements to a multipath routing, namely, path discovery, traffic distribution, and path maintenance. Path discovery involves finding available paths using pre-defined criteria. A popular metric is path disjointness, a measure of resource diversity between paths. Traffic distribution strategy defines how concurrently available paths are used, and how data to the same destination is split and distributed over multiple paths. Path maintenance specifies when and how new paths are acquired if the states of currently available paths change. There are numerous multipath routing protocols proposed for wireless ad hoc networks, exploring characteristics in mobility, interference, topology, etc. We present a selection of these protocols and give a discussion on how multipath techniques can be extended to wireless mesh networks. Lastly we briefly describe the path selection framework in the current proposal for IEEE 802.11s mesh standard. Although the proposal does not define use of multipath routing, its extensible framework for path selection provides provision for such protocols to be implemented.

1 Introduction

Multipath routing is a technique that exploits the underlying physical network resources by utilising multiple source-destination paths. It is used for a number of purposes, including bandwidth aggregation, minimising end-to-end delay, increasing fault-tolerance, enhancing reliability, load balancing, and so on. The idea of using multiple paths has existed for some time and it has been explored in different areas of networking.

In the traditional circuit-switching network, alternate path routing [1] was used to decrease the probability of call blocking. In this scheme, the shortest path between two exchanges is used until it fails or reaches its capacity, when calls are routed through a longer, alternate path[2].

In data network the idea of using multiple paths for end-to-end transport first appeared in [2]. One of the earliest distributed multipath algorithm was formulated by Gallager [3]. Based on the assumption of stationary input traffic and unchanging network, the computation framework converges to minimise the overall delay in the network. The major drawback of Gallager's algorithm is that it is very difficult to implement in the real world, given that each router needs to have knowledge of a global constant, which is impossible to determine for all conditions [4]. Also since the adjustment of parameters in each router is initiated by the destination and is done in iterations, the algorithm tends to converge slowly, or does not converge at all, therefore restricting its use for networks with stationary or quasi-stationary traffic. For these reasons, Gallager's method is used for obtaining theoretical lower bounds only. A number of improvements to the algorithm have since been proposed. In [5] an extension of Gallager's algorithm using second derivatives were proposed to improve the speed of convergence and parameter selection.

In the ATM PNNI standard [6], alternate paths may be set up during the reservation process. When a call fails on a route, the crankback process is started to try multiple alternate paths until a new route is established. In the Internet, some router implementations may support multiple paths with routing protocols such as RIP and OSPF. However, the paths are restricted to having equal-costs only.

1.1 Wireless Ad hoc and mesh networks

A mobile ad hoc network is formed by a collection of wireless mobile nodes without the support of fixed base stations or infrastructure. Every node shares its resources and participates in the routing of messages. Since transmission is wireless and nodes are mobile, ad hoc networks brought new challenges to the design of routing algorithms. Routes are more easily broken due to interference and node mobility, and nodes have limited bandwidth, energy, and processing power. These problems make multipath routing an possible solution. Already, numerous of multipath routing protocols have been proposed for ad hoc networks to increase routing performance.

The wireless mesh networks (WMN) technology have been gaining momentum lately because of its advantage in certain application areas such as community networks and enterprise backbones [7, 8, 9]. A WMN may consist of mobile clients and stationary mesh routers. A network of mesh routers can be used to provide infrastructure/backbone services to mesh clients. Such a network is called a Infrastructure WMN (IWMN) [7]. Although IWMN is similar to ad hoc networks in some respects, such as both being multi-hop wireless networks, there are a few important distinctions that warrant different routing strategies. Firstly, since mesh routers are stationary, mobility is no longer a problem. This means network topology change is less frequent than in ad hoc networks. Secondly, mesh routing protocols do not have energy consumption restrictions, since mesh routers should most likely be on wired power. Thirdly, the traffic distribution in a WMN is generally skewed. This is because most user traffic are directed towards/from Internet gateways or application servers on the network [10]. Finally, the IMWN demands better scalability, robustness and a range

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[2] In this paper we use the terms path and route interchangeably in the context of data networks

of other metrics in order to effectively provide backbone/ infrastructure services.

The remainder of the paper is organised as follows. In section 2, we give a background on multipath routing. A number of multipath routing protocols designed for ad hoc networks are then presented in section 3. In section 4 we discuss how multipath routing can be applied to IWMN routing and present the current progress in this area. We also discuss about the applicability of multipath routing in the current proposal of 802.11s mesh standard. The paper is concluded in section 5.

2 Multipath Routing

As mentioned before, multipath routing can provide a range of benefits. In the section we describe how these benefits are achieved, and give an overview of the main elements in multipath routing protocols.

2.1 Benefits of multipath routing

Fault tolerance – Multipath routing protocols can provide fault tolerance by having redundant information routed to the destination via alternative paths. This reduces the probability that communication is disrupted in case of link failure. More sophisticated algorithms employ source coding [11] to reduce the traffic overhead caused by too much redundancy, while maintaining the same degree of reliability. This increase in route resiliency is largely depended on metrics such as the diversity, or *disjointness*, of the available paths. We delay the discussion on disjoint routes until the next section.

Load balancing – When a link becomes over-utilised and causes congestion, multipath routing protocols can choose to divert traffic through alternate paths to ease the burden of the congested link.

Bandwidth aggregation – By splitting data to the same destination into multiple streams, each routed through a different path, the effective bandwidth can be aggregated. This strategy is particular beneficial when a node has multiple low-bandwidth links but requires a bandwidth greater than an individual link can provide. End-to-end delay may also be reduced as a direct result of larger bandwidth.

Reduced delay – For wireless networks employing single path on-demand routing protocols, a route failure means that a new path discovery process needs to be initiated to find a new route. This results in a route discovery delay. The delay is minimised in multipath routing because backup routes are identified during route discovery.

2.2 Elements of a multipath routing protocol

There are three elements of multipath routing: path discovery, traffic distribution, and path maintenance.

PATH DISCOVERY

Path discovery is the process of determining the available paths for a source-destination pair. There are various criteria a protocol can use when deciding which subset, if not all, of possible paths it wants to find out in the discovery process.

Disjoint paths - The most commonly used criterion is the *disjointness* of paths, which classifies the independence of paths in terms of shared resources. There are three main types of path disjointness, namely *non-disjoint*, *link-disjoint*, and *node-disjoint*. A set of node-disjoint paths have no common nodes except the source and the destination. Similarly, link-disjoint paths have no common links, but may share some common intermediate nodes. And Non-disjoint paths can have links (and therefore nodes) in common. Note that node-disjointness implies link-disjointness. Provided they are available, node-disjoint paths are usually preferred because they utilise the most available network resources, therefore are the most fault-tolerant. In principle, when an intermediate node in a set of node-disjoint paths fails, only the path containing the failed node is affected, so there is minimum impact to the diversity of the routes. A link failure will only bring down one of multiple paths, whether they are link-disjoint or node-disjoint. However, a node failure could disable multiple links and break multiple link-disjoint paths. Non-joints paths offer the least degree of fault-tolerance as either node or link failure could affect multiple paths.

It is not always possible to find disjoint routes, especially when the choice of routes is limited. In this scenario, protocols often use the notion of *maximally disjointness* to minimise the chance of a link or node failure affecting multiple paths.

On wireless networks, because of the significant performance impact of using multiple hops, node-disjoint paths may not be the best solution if the paths consist of too many hops. This trade-off between availability and performance should be considered when design multipath protocols for multi-hop wireless networks.

Route coupling – It was shown in [12] that in wireless networks, route coupling caused by radio interference or contention between paths can have serious impacts on the performance of multipath routing protocols, even if the paths are topologically disjoint. In a wired network route coupling is gauged by path disjointness, but in a radio network routes are also considered heavily coupled if transmission on one route directly impedes the qualities of that of the other. Route coupling can be alleviated by making changes at the physical/link layers, such as using multiple channels [12], or directional antennae [13].

TRAFFIC DISTRIBUTION

There are various strategies of allocating traffic over available paths. A multipath protocol may decide to forward traffic using only the path with the best metric and keep other discovered paths as backups. Or the paths may be used concurrently. Path selection algorithm is used to select a subset of available paths according to certain quality of the paths. *Hop-count* has traditionally been a popular metric to use. Some other choices are: path reliability, disjointness, available bandwidth, degree of route coupling, or a combination of metrics. In QoS routing, a subset of paths is only selected if the combined metric satisfies the QoS requirement.

Number of paths – A protocol can choose to use a single path and keep the rest as backups, or it can utilise multiple paths in a round-robin fashion, with only one path sending at a time. If multiple paths are used concurrently to carry traffic, the protocol needs to decide how traffic is split over the paths and how to handle out-of-order packets at the destination. It is also possible to add a degree of redundancy when distributing traffic over multiple paths. A *M-for-N diversity coding* scheme is described in [11]. In this coding scheme, *M* extra transmission lines are used to increase redundancy of an *N*-transmission-line system. The traffic over the M + N is coded in a way such that the system can tolerate less than M simultaneous line failures at any time. This idea is extended to multipath routing in packet networks in [14].

Allocation granularity – Some possible choices of traffic granularity include, in order of increased control overhead, per source-destination pair, per flow, per packet, per segment. With a fine granularity, load balancing can be more efficient, since traffic fluctuation can be adapted to quickly [15]. Nevertheless, per packet or finer granularity require reordering at the destination, which may not suit some applications.

PATH MAINTENANCE

Over time, paths may fail due to link/node failures or, in ad hoc networks, node mobility. Path maintenance is the process of regenerating paths after the initial path discovery. It can be initiated after each path failure, or when all the paths have failed. Some multipath protocols use dynamic maintenance algorithms to constantly monitor and maintain the quality or combined QoS metric of available paths.

3 Multipath Routing Protocols for Wireless Ad Hoc Networks

Numerous multipath routing protocols have been proposed for wireless ad hoc networks. Many of them based on the popular on-demand routing protocols, DSR [16] and AODV[17]. In this section we will present a selection of them.

3.1 Protocols based on DSR

Extension by Napsipuri and Das – A multipath extension to DSR is presented in [18]. The main motivation of this work is to reduce and efficiently control the frequency of route discovery floods, since these intrinsic parts of on-demand protocol takes up a significant amount of available network bandwidth. The paper presents two slightly varied versions of multipath extensions and an analytical model for evaluating the quality of on-demand protocols.

The protocols define *primary* source route as the route identified by the first Route REQuest (RREQ) message to reach the destination. It is relied on that the primary route represents the shortest route most of the time. Once the primary route is identified, the destination will only reply to those subsequent RREQ messages containing route that is *link-disjoint* to the primary route. Initially, traffic is routed via the primary route. When a route fails, the protocol switches to the shortest backup route. A new route discovery is initiated when all routes have failed.

In protocol 1 of the extension, only the source node is given the choice of alternate routes, therefore any intermediate link failure will cause a temporary loss of route until the source receives an error message and switches to a new route. Consequently all packets to the destination upstream from the failed link will be lost for the duration of the loss of route.
Protocol 2 alleviates this problem by allowing intermediate nodes to have one alternate route and switch route as soon as the primary fails (Figure 1). During the route discovery process, the destination attempts to supply each intermediate node in the primary route with a link-disjoint alternate to the destination. When a link fails, the first upstream node with an alternate route consumes the error message and switches route for all subsequent traffic. This process continues until the source node receives a route error, when a new route discovery is started.

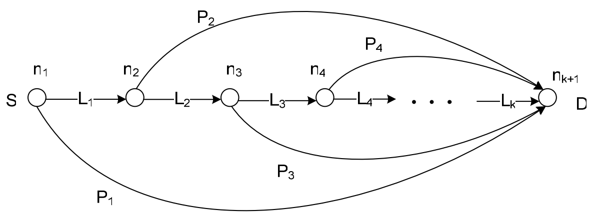

Figure 1 Alternate routes in [18]. The primary route consists of L_1, L_2,…, L_k. Each node in the primary route n_i, has an alternate path *Pi* to the destination.

The authors concluded, after performing numerical analysis that, 1. Any form of multipath outperforms single path routing in terms of frequency of route rediscovery, and 2. Longer alternate paths are less beneficial and the performance gain is the less significant using more than two alternate routes.

Split Multipath Routing (SMR) [19] is a also multipath version of DSR. Unlike many prior multipath routing protocols, which keep multiple paths as backups routes, SMR is designed to utilise multipath concurrently by splitting traffic onto two *maximally disjoint* routes. Two routes said to be maximally disjoint if the number of common links is minimum [20].

In SMR, intermediate nodes do not reply to RREQs even if they have routes to the destination. This is so to increase the number of RREQs received at the destination. In addition, intermediate nodes forward those RREQ packets received from a different link to the one from which the first RREQ is received, provided its hop count is less than the first RREQ (i.e. has a better metric). This further increase the number of routes received by the destination, although this comes at a cost of increased control overhead. As with [18], the shortest delay route, identified by the first RREQ to arrive at the destination, is used. The destination then selects the second route as the one that is maximally-disjoint to the first route. The authors opted for a *per-packet* granularity for allocating traffic, arguing that the difficulty of obtaining network condition of an ad hoc network prevents the use of more sophisticated allocating schemes.

When a route fails, every entry, regardless of destination, in the source’s routing table that shares common intermediate nodes with the fail route is removed. After this if the other route remains valid, either a new route discovery is initiated, or the protocol waits until the second route fails, too. It was shown in simulation that SMR outperforms DSR in terms of delay and packet drops in an ad hoc network. Furthermore, SMR is more efficient when new route discovery is initiated only when both routes are broken, as this scheme generates less control overhead.

MP-DSR [21] was designed with Quality-of-Service in mind. It’s aimed at providing QoS support in terms of *end-to-end reliability*, defined as *the probability of having a successful data transmission between two mobile nodes within the time period from t_0 to $t_0 + t$, where t_0 is any time instant*. Mathematically, this is defined as,

$$P(t) = 1 - \prod_{k \in K} (1 - p(k,t))$$

where K is a set of node-disjoint paths from the source to the destination. $p(k,t)$ is the *path reliability* of path k, calculated as the product of *link availability* of all the links in path k. In other words, $P(t)$ is the probability that at least one path stays connected for the duration of t. Given an end-to-end reliability requirement, the protocol determines the number of paths, m_0, it needs to discover, each of which has to support a minimum path reliability requirement. The route discovery process is started by the source sending out m_0 RREQ messages. When an intermediate node receives a RREQ, it checks whether the path reliability of the path identified by the RREQ so far still satisfies the required path reliability. If so the RREQ is forwarded to a maximum of m_0 neighbours, otherwise it is discarded. The destination receives all the RREQs, and selects a set of node-disjoint paths that combine to satisfy a defined reliability requirement. The set of multiple paths the destination note chooses is not necessarily the optimum set; the first combination that satisfies the requirement gets selected.

	[18]	**SMR** [19]	**MP-DSR** [21]	**AOMDV** [22]	[14]	**MPR-E** [13]	**ROAM**[23]
Base Protocol	DSR	DSR	DSR	AODV	Diversity coding		DUAL [24]
Source or Distance-Vector routing	source	source	source	DV	source	DV	DV
Route discovery	multiple link-disjoint routes	shortest delay path and it's maximally-disjoint route	set of maximally-disjoint paths that satisfy QoS requirement	link- or node-disjoint paths	node-disjoint	maximally zone-disjoint shortest paths	non-disjoint
Routing choice made at	source and intermediate nodes	source	source	intermediate nodes	source	intermediate nodes	intermediate nodes
Traffic distribution	single path	two paths concurrently	not specified	single path	multipath concurrently	two paths concurrently	single path
Allocation granularity	n/a	Per packet	n/a	n/a	block	packet	n/a
Route maintenance	New discovery when all exhausted	**i**. immediately attempt new discovery **ii**. only when both fail	**i**. all paths broken **ii**. QoS no longer satisfied	when last path fails	when QoS requirement no longer satisfied	n/a	on change of link distance
Motivation/ Application	reduce frequency of route discovery floods	splitting traffic provides better load distribution	QoS applications with soft end-to-end reliability	discovers disjoint paths without using source routing	enforce end-to-end error rate QoS	Increase throughput	wired/wireless networks with static nodes

Table 1 Summary of multipath routing protocols presented

MP-DSR periodically checks the end-to-end reliability to ensure the qualities of the routes. A new route discovery is initiated when either the reliability is no longer deemed acceptable, or when all paths fail. It was shown in simulation that MP-DSR has better success delivery rate, control overhead ratio, and error ratio, over DSR in a 20 mobile node network.

3.2 Protocols based on AODV

AOMDV [22] offers an multipath, loop-free extension to AODV. It ensures that alternate paths at every node are disjoint, therefore achieves path disjointness without using source routing.

To support multipath routing, route tables in AOMDV contain a list of paths for each destination. All the paths to a destination have the same destination sequence number. Once a route advertisement with a higher sequence number is received, all routes with the old sequence number are removed. Two additional fields, *hop count* and *last hop*, are stored in the route entry to help address the problems of loop freedom, and path disjointness, respectively.

Because the protocol implement multipath discovery, the loop-freedom guarantee from AODV no longer holds. AOMDV address this issue as follows. The hop count field contains the length of the *longest* path for a particular destination sequence number, and is only initialised once, at the time of the first advertisement for that sequence number. Hence, the hop count remains unchanged until a path for a higher destination sequence number is received. It follows that loop freedom is ensured as long as a node never advertises a route shorter than one already advertised, and never accepts a route longer than one already advertised.

To ensure that paths in the route table are link-disjoint, a node discards a path advertisement that has either a common next hop or a common last hop as one already in the route table. It was observed that, as long as each node adheres to this rule, all paths for the same destination sequence number are guaranteed to be link-disjoint. Node-disjoint paths can be obtained with an additional restriction that for a particular destination sequence number, every node always advertises the same designated path to other nodes. Route maintenance in AOMDV is similar to that in AODV. A RERR for a destination is generated when the last path to that destination fails.

3.3 Other approaches

TORA – The Temporally-Ordered Routing Algorithm (TORA) [25] is based on [26], and is designed to decouple control message overhead from network topology changes to the greatest extent possible. TORA is reactive and distributed. It uses a link reversal algorithm to achieve a destination oriented directed acyclic graph (DAG) that is guaranteed to be loop-free. Multiple paths are established using QRY/UPD message exchanges similar to that in DSR/AODV. No distance metric or link-state information is exchanged between nodes in order to minimise control traffic. However, a drawback of this approach is that as link reversal process continues over time, routing may become less optimal than it initially was. TORA also requires nodes in the network to be time synchronised, as it uses time stamps (tagging). Performance studies [27] have shown that the algorithm is prone to congestion since it requires timely and reliable routing control message delivery.

ROAM – [23] presents an on-demand distance-vector algorithm called Routing On-demand Acyclic Multipath (ROAM). It is basically a multipath version of DUAL [24], which uses a concept called *feasible distance* to maintain routes and loop freedom. ROAM detects network partitions by requiring nodes to send update messages to neighbouring routing whenever change in distance to a certain destination exceeds a predefined threshold. Since the algorithm requires the exchanges of state information between nodes, it is more suitable for use in static networks or networks with limited mobility.

Diversity coding – A framework for multipath scheme in ad hoc networks is proposed in [14]. The scheme is based on *M-for-N diversity coding* [11] described earlier. In this scheme, a packet of N equal block size is added with additional overhead calculated as a linear function of the original packet. The combined data and overhead is fragmented into $M + N$ blocks and allocate over multiple node-disjoint paths to the destination. Instead of allocating one block on M + N paths, the scheme allows multiple blocks to be assigned to a single path. Each path is assigned a probability of failure, p_i, such that either no information is received at the destination with probability p_i, or all information is received correctly with probability $1-p_i$. The available node-disjoint paths to a destination are ranked by failure probability, and only a subset of the lowest p_i is used for routing. The scheme proposes an optimisation algorithm to determine the number of highest ranked paths to used and the block allocation to each path, so that the probability of reconstructing the original packet at the destination is maximised. The complexity of the algorithm can be reduced by approximation. This provides provision for real time monitoring of QoS metrics to determine when route discovery is reinitiated. It was observed in [14] that as the number of paths increases, the probability of success delivery approaches 1. In real ad hoc networks, however, it might be difficult to discover more than a handful of node-disjoint paths unless the network is dense.

MPR-E – MultiPath Routing with EAPAR [13] aims to address the problem of route coupling caused by interference and contention in wireless networks. It uses the notion of *zone-disjointness* as the main path selection criteria. A pair of paths are said to be zone-disjoint if the data transmission over one path does not interfere with that over the other. To further increase routing performance, the protocol tries to limit the length of paths (in term of hops) by finding maximally zone-disjoint shortest paths.

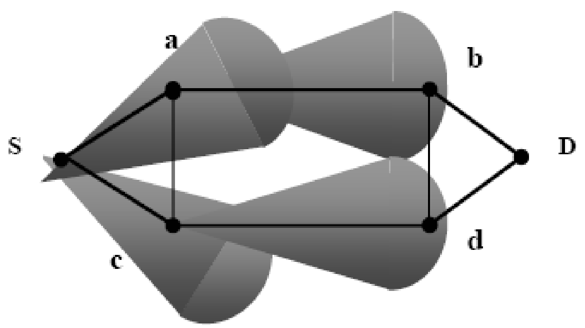

Figure 2 Zone-disjoint multipath communication between S and D, as illustrated in [12]

Because omni-directional antenna creates unwanted interference in all directions, MPR-E adopts directional antenna to reduce the effective *transmission zone* of each node, and there maximising the availability of zone-disjoint paths in the network. The antenna studied is called ESPAR (Electronically Steerable Passive Array Radiator). When idle, the antenna stays in omni-directional-sensing mode, until each node in the network contains information perceived by it about the network topology and communication activities. When a source has information to send to a destination, it tries to forward packets alternately onto two maximally zone-disjoint paths. Each intermediate node will try to avoid forwarding onto busy hops. As packet is passed downstream, the change that it is forwarded using the shortest path is increased. It is shown that MPR-E offers better throughput than AODV, especially as mobility increases.

4 Multipath Routing in Wireless Mesh Networks

Multipath routing in infrastructure mesh networks requires a different approach to that used in ad hoc networks to address the presence of stationary backbone routers. In this section we look at two areas of research where we consider multipath routing has great potential in improving performance in infrastructure mesh routing.

Multi-radio, multi-channel

As the cost of hardware comes down, multi-radio and multi-channel technologies are deemed by many as a viable solution to some link capacity and reliability issues [28]. Since infrastructure mesh routers have less cost, energy and resource restrictions than ad hoc nodes, the application of the technology to in IWMN seems particularly attractive [7].

Numerous studies [10, 29, 30, 31] have been presented on the capacity and characteristics of network using multi-radio and multi-channel nodes. In [32] a new metric for routing in multi-radio, multi-hop networks is presented. The metric, called Weighted Cumulative ETT (WCETT), was designed to be used to select channel diverse paths. It is based on Expected Transmission Time (ETT), a function of the loss rate and the bandwidth of the link, and calculates a weighted average of EETs of links in a path. [33] improves upon the single-path selection in [32] and presented a metric for selecting multiple paths. Channel Aware Multipath (CAM) considers both single path WCETT and an inter-path interference index, so that route coupling can be reduced.

The above studies into multipath routing concentrate on network measurements as path selection metrics. Although channel diversity is increased, spatial diversity is ignored and path reliability could suffer as a result. Future work in this area could include the study of algorithms that incorporate topological disjointness and multi-channel metrics.

Geographic Routing

Geographic routing protocols [34, 35, 36] utilise location information such as coordinates to forward packets. The location of the source, the destination, and neighbour nodes are used to make forwarding decisions. Geographic routing protocols typically have good scalability, since little or no routing information is exchanged in the network. However, before routing a packet, the source node needs to collect the location of the destination. As such, an efficient and scalable location service is crucial to the performance of geographic routing, and there have been numerous solutions [36, 37, 38].

In infrastructure WMNs, since nodes are stationary, there is very little need for frequent location updates. Therefore the performance of location service no longer dictates the effectiveness of routing. Multipath routing protocols can benefit from geographic routing in that location information can be used to construct a more accurate network topology, so that disjoint paths are more easily identified.

4.1 *802.11s Mesh Standard Proposal*

802.11s [39] is the IEEE 802.11 standard for wireless LAN mesh networking. The current proposal specifies an extensible framework for layer two path selection protocols support. Apart from the mandatory protocol and metric that all implementation must support for interoperability reasons, the framework allows additional protocols and metrics to be implemented.

The default path selection protocol in the 802.11s proposal is Hybrid Wireless Mesh Protocol (HWMP). It supports both on-demand and proactive tree-based routing. The baseline on-demand protocol is called Radio Metric AODV (RM-AODV). It extends AODV [17] to supports use of arbitrary path metrics in identifying best-metric paths. When a network entity called Root is present in the mesh, a proactive distance vector routing tree can be maintained. Since the Root knows route to all nodes in the mesh, a path between two nodes can be established quickly by querying and routing through the Root. The low path discovery delay in this scheme means that the proactive path can be used during on-demand route discovery process.

Although the 802.11s proposal does not support multipath in its baseline protocol, the path selection framework can be easily extended to include multipath enabled protocols and metrics. The mesh nodes can switch between protocols according to their application needs. Given this, how multipath routing can be adapted into the current proposed mesh network architecture/hierarchy remains to be investigated.

5 Conclusion

In this paper we present the concept of multipath routing with emphasis on its applications on wireless ad hoc and mesh networks. We have listed the benefits of employing multipath algorithms in routing, and described its three elements, namely path discovery, traffic distribution, and path maintenance. We also provide descriptions of a number of multipath routing schemes proposed for wireless ad hoc networks, aiming at showing various strategies of utilising multiple routings in wireless networks. A summary of these protocols is given, highlighting their features and characteristics. We have identified several areas in infrastructure wireless mesh networks that require further work. Current multipath routing research focus on multi-radio and multi-channel nodes is to provide improved metrics for path selection and also to address channel assignments and switching. One possible direction is to combine channel and spatial diversity into path selection algorithms. Finally, we examined path selection framework in the joint 802.11s proposal. While the default protocol does not utilise multipath techniques, the extensible framework means that new multipath protocols and related metrics may be easily added to support specific applications.

References

[1] B. Hurley, C. Seidl, and W. Sewell, "A survey of dynamic routing methods for circuit-switched traffic," *Communications Magazine, IEEE*, vol. 25, pp. 13-21, 1987.

[2] N. F. Maxemchuk, "Diversity Routing," in Proc. IEEE ICC, San Francisco, CA, 1975.

[3] R. Gallager, "A Minimum Delay Routing Algorithm Using Distributed Computation," *Communications, IEEE Transactions on [legacy, pre - 1988]*, vol. 25, pp. 73-85, 1977.

[4] S. Vutukury and J. J. Garcia-Luna-Aceves, "A simple approximation to minimum-delay routing," in *Proceedings of the conference on Applications, technologies, architectures, and protocols for computer communication*. Cambridge, Massachusetts, United States: ACM Press, 1999.

[5] D. Bertsekas, E. Gafni, and R. Gallager, "Second Derivative Algorithms for Minimum Delay Distributed Routing in Networks," *Communications, IEEE Transactions on [legacy, pre - 1988]*, vol. 32, pp. 911-919, 1984.

[6] "Private Network-Network Interface Specification v.1.1," ATM Forum, 2002.

[7] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Computer Networks*, vol. 47, pp. 445-487, 2005.

[8] StrixSystems, http://www.strixsystems.com/

[9] Firetide, http://www.firetide.com/

[10] A. Raniwala and T.-c. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE, 2005.

[11] E. Ayanoglu, I. Chih-Lin, R. D. Gitlin, and J. E. Mazo, "Diversity coding for transparent self-healing and fault-tolerant communication networks," *Communications, IEEE Transactions on*, vol. 41, pp. 1677-1686, 1993.

[12] M. R. Pearlman, Z. J. Haas, P. Sholander, and S. S. Tabrizi, "On the impact of alternate path routing for load balancing in mobile ad hoc networks," in *Proceedings of the 1st ACM international symposium on Mobile ad hoc networking & computing*. Boston, Massachusetts: IEEE Press, 2000.

[13] D. Saha, S. Toy, S. Bandyopadhyay, T. Ueda, and S. Tanaka, "An adaptive framework for multipath routing via maximally zone-disjoint shortest paths in ad hoc wireless networks with directional antenna," Global Telecommunications Conference, 2003. GLOBECOM '03. IEEE 2003.

[14] A. Tsirigos and Z. J. Haas, "Multipath routing in the presence of frequent topological changes," *Communications Magazine, IEEE*, vol. 39, pp. 132-138, 2001.

[15] R. Krishnan and J. A. Silvester, "Choice of allocation granularity in multipath source routing schemes," INFOCOM '93. Proceedings.Twelfth Annual Joint Conference of the IEEE Computer and Communications Societies. Networking: Foundation for the Future. IEEE San Francisco, CA 1993.

[16] D. B. Johnson and D. A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks," in *Mobile Computing*, Imielinski and Korth, Eds.: Kluwer Academic Publishers, 1996.

[17] C. Perkins, "Ad hoc On-Demand Distance Vector (AODV) Routing," IETF RFC 3561, 2003.

[18] A. Nasipuri and S. R. Das, "On-demand multipath routing for mobile ad hoc networks," Computer Communications and Networks, 1999. Proceedings. Eight International Conference on, Boston, MA, 1999.

[19] S. J. Lee and M. Gerla, "Split multipath routing with maximally disjoint paths in ad hoc networks," ICC 2001. IEEE International Conference on Communications, Helsinki, 2001.

[20] N. Taft-Plotkin, B. Bellur, and R. Ogier, "Quality-of-service routing using maximally disjoint paths," Quality of Service, 1999. IWQoS '99. 1999 Seventh International Workshop on, London, 1999.

[21] R. Leung, J. Liu, E. Poon, A. L. C. Chan, and B. Li, "MP-DSR: a QoS-aware multi-path dynamic source routing protocol for wireless ad-hoc networks," Local Computer Networks, 2001. Proceedings. LCN 2001. 26th Annual IEEE Conference on, Tampa, FL 2001.

[22] M. K. Marina and S. R. Das, "Ad hoc On-demand Multipath Distance Vector Routing," Computer Science Department, Stony Brook University, 2003.

[23] J. Raju and J. J. Garcia-Luna-Aceves, "A new approach to on-demand loop-free multipath routing," Computer Communications and Networks, 1999. Proceedings. Eight International Conference on, Boston, MA 1999.

[24] J. J. Garcia-Lunes-Aceves, "Loop-free routing using diffusing computations," *Networking, IEEE/ACM Transactions on*, vol. 1, pp. 130-141, 1993.

[25] V. D. Park and M. S. Corson, "A highly adaptive distributed routing algorithm for mobile wireless networks," INFOCOM '97. Sixteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE, Kobe, 1997.

[26] E. Gafni and D. Bertsekas, "Distributed Algorithms for Generating Loop-free Routes in Networks with Frequently Changing Topology," *IEEE Transactions on Communications*, vol. 29, pp. 11-15, 1981.

[27] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols," in *Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking*. Dallas, Texas, United States: ACM Press, 1998.

[28] P. Bahl, A. Adya, J. Padhye, and A. Walman, "Reconsidering wireless systems with multiple radios," *SIGCOMM Comput. Commun. Rev.*, vol. 34, pp. 39-46, 2004.

[29] P. Kyasanur, S. Jungmin, C. Chereddi, and N. H. Vaidya, "Multichannel mesh networks: challenges and protocols," *Wireless Communications, IEEE [see also IEEE Personal Communications]*, vol. 13, pp. 30-36, 2006.

[30] M. Kodialam and T. Nandagopal, "Characterizing the capacity region in multi-radio multi-channel wireless mesh networks," in *Proceedings of the 11th annual international conference on Mobile computing and networking*. Cologne, Germany: ACM Press, 2005.

[31] A. Raniwala, K. Gopalan, and T.-c. Chiueh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 8, pp. 50-65, 2004.

[32] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," International Conference on Mobile Computing and Networking, Philadelphia, PA, USA, 2004.

[33] I. Sheriff and E. Belding-Royer, "Multipath Selection in Multi-radio Mesh Networks," Broadnets, San Jose, 2006.

[34] B. Karp and H. T. Kung, "GPSR: greedy perimeter stateless routing for wireless networks," in *Proceedings of the 6th annual international conference on Mobile computing and networking*. Boston, Massachusetts, United States: ACM Press, 2000.

[35] H. Li and M. Singhal, "A scalable routing protocol for ad hoc networks," Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st, 2005.

[36] Y.-B. Ko and N. H. Vaidya, "Location-aided routing (LAR) in mobile ad hoc networks," *Wirel. Netw.*, vol. 6, pp. 307-321, 2000.

[37] D. S. J. De Couto and R. Morris, "Location Proxies and Intermediate Node Forwarding for Practical Geographic Forwarding," *MIT Laboratory for Computer Science technical report*, 2001.

[38] C. T. Cheng, H. L. Lemberg, S. J. Philip, E. van den Berg, and T. Zhang, "SLALoM: a scalable location management scheme for large mobile ad-hoc networks," Wireless Communications and Networking Conference, 2002. WCNC2002. 2002 IEEE, 2002.

[39] "Joint SEE-Mesh/Wi-Mesh Proposal to 802.11 TGs," 2006.